TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ULLA-TALVIKKI VIRTA

MEASURING CYCLING ENVIRONMENT FOR INTERNET OF THINGS APPLICATIONS

Master's thesis

Examiners: Teemu Laukkarinen, D.Sc. and Professor Timo D. Hämäläinen

The examiners and topic of the thesis were approved on 9 December 2015

ABSTRACT

ULLA-TALVIKKI VIRTA: Measuring Cycling Environment for Internet of Things Applications
Tampere University of Technology
Master of Science Thesis, 57 pages
October 2018
Master's Degree Programme in Computing and Electrical engineering
Major: Wireless sensor networks
Examiners: Teemu Laukkarinen, D.Sc. and Professor Timo D. Hämäläinen

Keywords: bicylce environment, IoT, Internet of Things, crowdsourcing

Increasing population in cities creates increasing amount of traffic, which leads to emissions and traffic congestion. Smart Cities set out to solve the challenges urban cities face due to the increased population, using Internet of Things as means to monitor the assets as it allows non-traditional devices to connect as a part of global information network. At the same time, cycling has increased its popularity as an environmentally friendly as well as healthy transportation method. To further its usage, infrastructure in cities must support cycling as a serious transportation method. For this purpose, it is important to include bicycles to Smart City with measurements of cycling and its environment.

This thesis studies if it is possible to measure factors affecting cycling environment and assess route quality without using sensors built in bicycle frame. Decision to avoid sensors embedded in frame stemmed from incentive to have easily available and inexpensive measuring device, which does not bind the cyclists to use bicycles from specific brand or require them to purchase new bike if they are interested in participating in measuring. For evaluating the feasibility of cycling environment measuring, prototype called BikeBox was built and used during test drives. In addition, an online survey was held, which received answers from 97 cyclists. The survey queried about their cycling habits and preferences to better understand what kind of data they would be interested in.

The prototype included accelerometer for measuring road quality, photoresistor to identify poorly lit areas and GPS module for location and timestamps, which are needed for other measurements as well as finding possible stopping points and slow areas on the route.

Based on the test drives it is possible to identify quality changes on road surface as well as changes in lighting. Inaccurate GPS positioning does pose a challenge for pinpointing exact locations, though. Using location and timestamps it is possible to calculate the speed along different parts of the route, including areas which cause interruptions for the cyclists. This thesis presents results from 7 different example drives, though during testing phase more test driving was done. To get comprehensive coverage, crowdsourcing should be considered as the data gathering method. Based on the survey fastness and length of the route, amount of stops and interruptions and road condition are one of the most important factors for the cyclists. When queried what kind of information cyclists would like to receive, the road condition related factors were most commonly mentioned.

TIIVISTELMÄ

ULLA-TALVIKKI VIRTA: Pyöräilyn ympäristötekijöiden mittaaminen esineiden internetin sovelluksia varten
Tampereen teknillinen yliopisto
Diplomityö, 57 sivua
Lokakuu 2018
Tieto- ja sähkötekniikan diplomi-insinöörin tutkinto-ohjelma
Pääaine: Langattomat sensoriverkot
Tarkastajat: Teemu Laukkarinen, TkT ja professori Timo D. Hämäläinen

Avainsanat: pyöräilyn ympäristötekijät, esineiden internet, joukkoistaminen

Kaupungistumisen seurauksena väkimäärät kaupungeissa kasvavat, mikä tuo mukanaan kasvavat liikennemäärät, ruuhkat ja liikennepäästöt. Älykkäät kaupungit ovat reaktio kaupungistumisesta seuraaviin haasteisiin. Älykkäät kaupungit pyrkivät seuraamaan ja kontrolloimaan kaupungin infrastruktuuria, apunaan esineiden internet. Esineiden internet mahdollistaa epäperinteisten laitteiden yhdistämisen maailmanlaajuiseen tietoverkkoon. Samaan aikaan pyöräilyn suosio on kasvanut ympäristöystävällisenä ja terveellisenä liikennemuotona. Jos pyöräilyn määrää halutaan jatkossakin kasvattaa, kaupungin infrastruktuurin täytyy tukea pyöräilyä vakavasti otettavana liikennemuotona. Jotta tämä voidaan saavuttaa, on pyöräilijöiden pyöräily-ympäristön ja pyöräilytapojen ymmärtäminen tärkeää.

Tässä työssä tutkitaan, onko pyöräily-ympäristöön vaikuttavia tekijöitä mahdollista mitata sensoreilla, joita ei ole istutettu polkupyörän runkoon. Runkoon upotettuja sensoreita haluttiin välttää, jotta mittauslaitteet voisivat olla mahdollisimman suuren joukon saatavilla, eikä pyöräilijä olisi sidottu käyttämään tietyn valmistajan polkupyörää. Lisäksi pyritään selvittämään, minkälaisesta pyöräily-ympäristöön liittyvästä datasta pyöräilijät olisivat kiinnostuneita. Tähän tarkoitukseen rakennettiin prototyyppi PyöräPurkista (BikeBox). Lisäksi toteutettiin internet-kysely, johon vastasi 97 polkupyöräilijää. Kyselyllä selvitettiin pyöräilijöiden pyöräilytapoja ja -mieltymyksiä ja sitä, millainen pyöräily-ympäristöstä kertova data kiinnostaisi heitä.

Prototyyppiin sisällytettiin kiihtyvyysanturi tien pinnan laadun mittaamiseen, valoanturi heikosti valaistujen alueiden tunnistamiseen ja GPS-moduuli, jolla saadaan sijantitieto ja kellonaika muita mittauksia varten. Lisäksi sijaintitiedosta ja kellonajasta voidaan laskea ajonopeus ja paikat, missä pyöräilijä on joutunut keskeyttämään ajonsa.

Testiajojen perusteella on mahdollista havaita tien pinnanlaadun muutos sekä muutos valaistusolosuhteissa. Epätarkkuudet GPS-paikannuksessa vaikeuttavat kuitenkin ongelmakohtien tarkkaa paikallistamista. Tämä työ käsittelee aiheita 7 erillisen testiajon kautta, vaikka testausvaiheessa ajettiinkin useampia testiajoja. Kattavien mittausten saamiseksi joukkoistamista kannattaisi harkita datankeräysmetodina. Tehdyn kyselyn perusteella reitin nopeus, pituus, reitillä olevien keskeytysten määrä ja tien kunto ovat tärkeimpiä reitin laatuun vaikuttavia tekijöitä. Erilaiset pyöräilyreitin kuntoon liittyvät asiat kiinnostivat eniten kun kysyttiin, minkälaista dataa pyöräilijät haluaisivat saada.

PREFACE

This thesis was written in the laboratory of Pervasive Computing for work that was done during project studying smart traffic data in Tampere. I wish to thank my advisor Teemu Laukkarinen for relentless re-reading and valuable comments during the process and professor Timo D. Hämäläinen for his feedback. In addition, I would like to thank Teemu Erkkola for volunteering to do some of the test drives. Finally, I would like to thank my husband Jari Voutilainen for his support and patience, and for his help in bludgeoning the LaTeX to jolly co-operation.

In Tampere, Finland, on 20 November 2018

Ulla-Talvikki Virta

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

2G/3G/4G	Cellular technology generations
ABS	Anti-lock Braking System
Arduino	Electronic prototyping platform and microcontroller
ARM	Architectural Reference Model
Bluetooth	Bluetooth is wireless, low power short range communication technology.
CoAP	Constrained Application Protocol
CSV	Comma Separated Value
EDGE	Enhanced Data rates for GSM Evolution
EEPROM	Electrically Erasable Programmable Read-Only Memory
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HSDPA	High-Speed Downlink Packet Access
HTTP	Hypertext Transfer Protocol
I2C	Inter-Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
IoT	Internet of Things
ITU	International Telecommunication Union
LAN	Local Area Network
LTE	Long Term Evolution
M2M	Machine to Machine
MQTT	Message Queue Telemetry Transport
NB-IoT	NarrowBand IoT
OMA LWM2M	Open Mobile Alliance Lightweight Machine to Machine
REST API	Representational State Transfer Application Programming Interface
RFID	Radio-Frequency identification
SaaS	Software as a Service
Sand road	Road which base and surface are made of sand
Sanded road	Road which has layers of sand applied over the original surface to prevent slippery conditions during winter. Sand is generally swept away after slippery conditions have passed.

SIM	Subscriber Identity Module
SPI	Serial Peripheral Interface
SRAM	Static Random-Access Memory
SRS	Supplemental Restraint System
TCP/IP	Transmission Control Protocol/Internet Protocol
TDMA	Time Division Multiple Access
TWI	Two-Wire Interface
UART	Universal Asynchronous Receiver/Transmitter
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
URI	Uniform Resource Identifier
UTC	Universal Time Coordinated
WLAN	Wireless Local Area Network
WOAG	WSN OpenAPI Gateway
WPAN	Wireless Personal Area Network

1. INTRODUCTION

When cities grow in population, they also need to get smarter to manage the side effects of the increased population size. A concept of Smart City has been introduced to overcome these challenges [15] and they utilize Internet of Things solutions to monitor and control the infrastructure[26]. IoT connects the different assets city has to information network with the aim of collecting the data and controlling it from centralized place. In the same time, the popularity of cycling is increasing due to ecological incentives to find transport options to combustion engines as well as its health benefits compared to non-exercise means of transportation. Advancing the use of bicycles has made it into official targets, for example Finland aims to introduce 20 percentage growth in cycling and walking by year 2020 [45].

Other plans for using bicycles as serious transportation method have emerged, too. Examples from Finland include paramedics on bicycle and city of Helsinki is suggesting that part of the delivery vans from courier companies could be replaced with bicycle couriers, easing the distribution traffic in city center [4] [49]. If the aim is to increase the amount of cycling, the city's infrastructure needs to support cycling as a viable option. For that, a Smart City would need to understand and measure the infrastructure available for cyclists and understand what kind of needs the cyclists have.

1.1 Background

Smart City is a concept where city's infrastructure is monitored for resource optimization and maintenance planning. Real time data is provided by monitoring systems and built in sensors, and it can be used to improve decision making either by avoiding unnecessary actions or acting before one has emergency at hand [34]. The motivation for Smart Cities comes from the challenges increasing urbanization causes. Traffic control and congestion are examples of the challenges that growing cities need to solve [15]. Traffic causes emissions, noise and congestions cost money because of the delays and loss of productivity [32].

The example from city of Helsinki suggesting to change some of the delivery vans to courier bikes shows that bicycle usage could also be part of the solution for traffic problems in urban cities [49]. The quality of the cycling infrastructure is one of the most important factors when trying to increase the amount of cycling. Van Goeverden and Godefrooij give recommendations regarding the promoting of bicycling [63]. Infrastructure design should keep in mind coherence, directness, attractiveness, safety and comfort. Travel time minimization and allowing high average speeds and minimal delays in traffic lights, is important as well as low traffic stress from other traffic methods such as cars. It is also noted, that improving the perception of cycling infrastructure quality increases the bicycle usage.

To understand the needs of cyclists and to be able to monitor the cycling infrastructure for the Smart City, an IoT approach can be considered, where nontraditional ”things” are brought as part of global information network by equipping them with way to connect, sense their environment, and act upon the information with actuators [2]. The wide range of possible things and applications makes the IoT field varied, but on high level the functional components of IoT architecture can be divided in three blocks: the devices, the gateway and the back end, as depicted in Figure 1.

Different devices interact with their environment by sensing and acting. As the devices are often heterogeneous in their hardware and communication methods, gateway acts as intermediate so that the different things can connect to the back end, to send and receive data. Back end can offer services that are then based on the available data[41]. Considering bicycles as things and allowing them to connect to internet while gathering data from their environment allows the information to be used to improve the conditions as well as to communicate about the quality of the infrastructure or to offer useful services to cyclists.

1.2 Motivation and research questions

Currently cycling data is not widely available to provide Smart City services for bicycling. Sports trackers are commonly used, but as they are focused on the exercise, they do not gather much environmental data. There exists IoT bikes that have sensors built in frame [64]. However, it is unlikely that few manufacturers could reach crowds that could provide the amount of data that is needed, due to the price and limited options in such specialty bikes. In addition, embedded sensors exclude all currently owned, non-IoT bicycles and cyclists from the measuring crowd. Comprehensive data would require measurements from multiple different sources, so the solution should be easily available for most of the cyclists. Separate measuring device is a feasible solution for this problem.

From that position, three research questions were formulated for this thesis:

- Is it possible to measure environmental factors on cycling route using sensors that are not built in the frame of the bicycle
- Is it possible to make assessments about the route quality for IoT applications based on the measurements
- What kind of environmental data cyclists would be interested in

1.3 Methods and scope

To answer the research questions, this thesis approaches the topic with constructive method [44], exploring current status of cycling related IoT solutions and what has been done with vehicular environment measuring with crowdsourcing. In order to evaluate the feasibility of measuring environmental factors of cycling route a prototype called BikeBox was built as proof of concept. In addition, to better understand what kind of environmental data cyclists could be interested in, a online survey was conducted for 97 cyclists. The survey queried their cycling habits, road preferences and what kind of data they were interested in. The results from the survey can then be used to evaluate if BikeBox can contribute data that would interest cyclists.

The prototype built for this thesis measures thee axis acceleration with accelerometer, time and location with GPS and ambient light with photoresistor and air quality with optical dust sensor. However, the air quality sensor was not suitable for the task so information about air quality was not received. From the available sensors three use cases were identified: Identifying different road qualities, identifying poorly lit areas and identifying slow parts and stopping points on the route.

For IoT solutions on the move, the data transfer and communication method chosen is an important feature, and suitable wireless communication was identified as important requirements for the BikeBox. Therefore, a detailed analysis was conducted of possible communication methods and based on the analysis, 3G was chosen for the BikeBox.

The technical scope of this thesis is being able to measure environmental factors for cycling and getting data from the device to the gateway and from that to the back end, allowing for solution that would collect data from multiple separate sources. Technical details of back end are left out of the scope. This thesis aims to find out if environmental factors are recognizable from collected data, but does not aim to build mathematical models that would work in large scale, crowdsourced context. Wide scale crowdsourcing is left for future work. With online survey the aim is to understand what factors cyclists deem important while cycling and what are their thoughts about the concept of BikeBox.

1.4 Outline

This thesis is structured as follows: Chapter two discusses the current situation of bicycles and IoT, as well as what has been currently done with vehicle and road infrastructure related crowdsourcing. Chapter three describes about the identified use cases and requirements for the BikeBox. Fourth chapter discusses the design choices made for the BikeBox, especially for communication. The prototype and its components are further described in chapter five. The results from test drives and survey are presented in chapter six and results are discussed in chapter seven. Chapter eight summarizes the work.

2. BACKGROUND

This chapter gives short introduction about Internet of Things and discusses about the current situation with IoT solutions for cycling, exploring what work has been done in the field. In addition, this chapter discusses about the current proposals and ideas for vehicular crowdsourcing.

2.1 Internet of Things

International Telecommunication Union (ITU) defines Internet of Things (IoT) in their Recommendation ITU-T Y.2060 as ”global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies” [2]. Main requirements for ”things” are that they must be identifiable and be able to take part in communication networks.

The general, high level Internet of Things architecture presented in Figure 1 is divided in three categories: devices, gateway and back end [41]. Devices is heterogeneous group of appliances from sensors and actuators in industrial environment to smart phones. The devices may or may not communicate with each other, depending on the specific application in question. As the device domain is often unable to communicate to the Internet by itself, due to using communication methods and protocols which may not be compatible, a gateway layer is needed as adapter to transform the communication to suitable format. In Figure 1 gateway is shown to include adapters for Zigbee and Bluetooth communication, but it is not limited to those technologies. Depending on the application, the gateway might also have other functionalities such as local device management or data aggregation.

After the gateway the data will end up in the third functional category: back end [41]. The presented features in Figure 1 are examples, but back end would generally offer access to the information provided by the IoT devices by various means, including dashboards, different services and Application Programming Interfaces (API). Representational State Transfer (REST) API is a way to identify available resources, such as devices or sensors with Uniform Resource Identifiers (URI) [33]. It can be used to create uniform interface for different kinds of resources, which is advantageous considering the heterogeneous nature of IoT.

2.2 Cycling and Internet of Things

As the interest in IoT solutions have grown over years, vehicles, as important feature of our everyday life, have also been attractive area to create IoT services. Following section

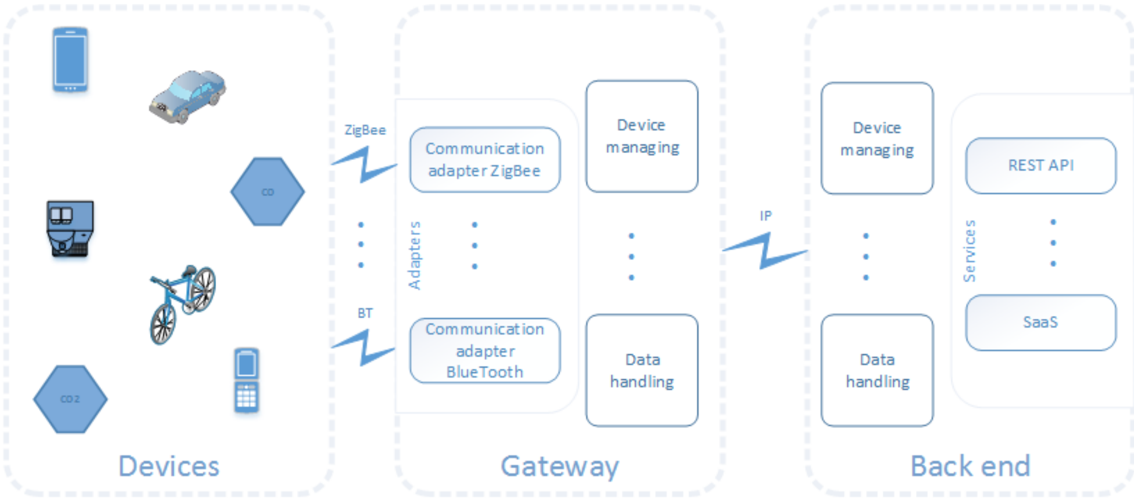


Figure 1. *General high level IoT-architecture*

discusses cycling related IoT solutions and services. The solutions are divided in three different categories: IoT bicycles, mobile applications for cyclists and external devices for cyclists. In this section main focus is on solutions that could be used by cyclists, services and solutions provided specifically for motoring are not discussed.

2.2.1 IoT bicycles

IoT bicycles refer to cases where the bicycle itself is equipped with sensors and possible radio modules or other connection methods. One example of such product is Valour IoT Bike manufactured by Vanhawks[64]. The bicycle has integrated navigation with handlebar indicators, it does automatic ride tracking and built-in lights react to ambient lighting, turning on when it is dark. Integrated sensors are gyroscope, accelerometer, magnetometer, speed sensor and GPS receiver and they are powered by the cycling itself. Bicycles can use WiFi to form a bicycle mesh, being able to share information between each other. Second example of interest towards IoT cycling is from Brompton, a folding bicycle manufacturer who has prototyped with IoT bicycle [40].

Embedding the sensor in the vehicle allows wider range of measurements and sensor can monitor more closely what the body of the bicycle is experiencing as there is no secondary attachment. However, as cyclists might be rather particular about bicycle features and cycling properties, it is less likely that single bicycle manufacturer can reach crowds that could cover large areas and produce data comprehensively. In addition, the cost of specialty bicycle might attract non-representative measuring crew, raising possibility of the cyclists and thus measuring results focusing on specific areas instead of covering the whole city. Having smart bicycles as rentable citybikes could alleviate these problems.

2.2.2 Mobile applications

In the mobile applications side, exercise trackers are wide spread example of IoT serviced provided for cyclists. Exercise trackers are applications that are meant for personal use and concentrate on measuring the exercise related data. This includes location, route length, speed, elevation and health data such as heart rate. While they are not concentrating on the cycling environment, part of the data, such as speed, route usages and elevations can provide information about the cycling environment.

There are currently available various sports trackers, which provide exercise related information such as route, speed and elevation. Examples of such applications are Sports Tracker [57], Endomondo [22] and HeiaHeia [35]. In addition different activity trackers and heart rate monitors offer mobile applications to go with the device.

2.2.3 External devices for bicycles

External devices refers to products that are not installed to the bicycle originally but must be acquired separately and either installed or otherwise attached to the bicycle. External device can have supporting mobile application, but differentiating from the mobile applications-category, the device is essential part of the product. This category can cover wide range of different devices, including:

- Smart locks, such as Bitlock [9] and Ellipse [21] provide keyless locking and make bicycle sharing possible.
- Theft alarms with bicycle trackers, such as Sherlock [54] or Cricket [60] notice if the bicycle is moved when it's not supposed to and can alert the owner. They can also show the location of the bicycle. Boundaries between device types are not rigid, smart lock can also include some theft alarm or monitoring features. Theft alarm might be included in other bicycle accessories too, such as lights.
- Dash cameras for bicycles, such as Cycliq [17]

Many of these devices have at least GPS in them and they can have other sensors too, for example to identify if the bicycle is fiddled with. However, it does not seem that they currently gather cycling environmental related data.

2.2.4 Related academic work

Possibilities of combining IoT with bicycles has attracted academic studies in addition to commercial undertakings. Flüchter and Wortmann conducted a field study and structured interviews with 32 participants to assess both technical challenges as well as consumer reception of gathering location data from bicycle drives [24]. 32 participants were given electric bicycles with GPS units that sent the location over GSM connection. As the units were powered by the electric bicycle's battery, the participants reported battery drainage due to the additional devices. They also noticed challenges of determining if the GPS data was complete or only covered part of the trip. Software changes could alleviate both of these problems. From the interviews Flüchter and Wortmann gathered that users are quite highly interested in data provided by the electric bicycles, though the interest and willingness to share the data to the bicycle manufacturer seems to be affected by how good quality data and derived information they themselves receive at the same time. From BikeBox point of view, that notion is important, as it suggest that being able to gather data from the cyclists, something must be provided for the cyclists in return.

In 2010 paper ”The Copenhagen Wheel: An innovative electric bicycle system that harnesses the power of real-time information and crowd sourcing” Outram, Ratti and Biderman discuss product under development that would turn a regular bicycle to electric bicycle including some IoT features such as intelligent locking, anti-theft mechanism, environmental sensors such as carbon monoxide, nitrogen oxides, temperature, noise and humidity which are controlled by smart phone [47]. However, currently as the product is on sale, it seems that the environmental sensors are not part of the final product features [16]. Based on the available material it seems that the Copenhagen Wheel does have sensors that monitor the state of the wheel, confirming that the wheel is operating inside safe temperature limits or gathering ride specific information such as rider torque, but does not offer environmental data from the bicycle ride.

Eisenman et al prototyped BikeNet, a system where bicycles and the riders were fitted with multiple sensors in different parts of the bicycle frame [20]. Sensors and measured aspects included microphone, carbon dioxide, speedometer/odometer, galvanic skin response stress monitor, lateral tilt, inclinometer, pedal speed, GPS and magnetometer. The architecture of the BikeNet is formed from the bicycles with sensors, Sensor Access Points (SAP), which are either static or mobile collection points for the data and the backend servers. The data is transferred either by the bicycle uploading data to mobile or static SAP when in range or by muling it to other bicycles when outside the range of SAPs.

During their project, five sensor bicycles were implemented and seven static SAPs were placed. Data was gathered from three cyclists from single drive. From the gathered data they provide examples of both raw data and ways to interpreting the cyclists’ experience by defining couple of metrics: Health index that depends on car density, co2 level and sound level and enjoyment metric which depends on the hill angle.

From these cases, the Eisenman et al are most aligned with concept of BikeBox as much of the focus is on environmental measurements, though they approach the subject with different architectural and physical solutions, requiring dedicated infrastructure to be on place and distributing the sensors around the frame of the bicycle, making the project closer to dedicated IoT bicycles.

2.3 Crowdsourcing

Measuring cycling environment means measuring areas and events that are not confined in predetermined and easily controllable locations such as factories or homes. Service providers, cities or other interested agents, have to distribute sufficient amount of sensing devices over areas that are widespread, public and possibly outside the official control of the service providers if the service provider is not the city or municipality. One solution is to distribute the devices to the general public, crowdsourcing the sensing.

This section discusses about other vehicle and road condition related projects and papers that are based on the premise of crowdsourcing the data. In addition, this section outlines potential privacy and security issues present while crowdsourcing sensitive data such as location.

2.3.1 Crowdsourcing based solutions and proposals

Crowdsourcing has been proposed as a data gathering method in use cases that are similar to BikeBox's use cases but aimed for cars. For example Fox, Kumar, Chen and Bai discuss about detecting potholes using the existing sensors in the cars and crowdsourcing the data [25]. They used both simulated data and data from test drives, which were 6.6 km long laps driven 8 times for both lanes, for creating the model for the pothole detection. They also demonstrate from their real life test data that the detection rate grows as the number of data providing vehicles grow, giving motivation to crowdsource the data for better detection rates.

Chen, Lu, Tan and Wu also discuss road surface monitoring system for cars that would base its data gathering to crowdsourcing [14]. Their use cases include both pothole detection and road surface roughness evaluation. They fitted 100 vehicles with device that included three axis accelerometer, GPS and GMS modules. In addition they had a vehicle recording video about the road surface reality. They classified the road roughness levels in smooth, general, bumps and potholes based on the acceleration data. Other crowdsourcing suggestion for finding potholes include mobile application by Carrera, Guerin and Thorp where accelerometers in mobile phones are used to detect potholes from the cars [13].

Another example of plans for vehicular crowdsourcing is from Mathur et al [46]. They presented a ParkNet where cars fitted with ultrasonic rangers can be used to detect if there are roadside parking spaces available. Testing was done with three cars producing over 500 miles (over 805km) of test driving during the normal commute usage of the cars. In addition, they analyzed mobility data from San Francisco taxis to determine if fitting taxis with rangers would be more cost effective solution for detecting free parking spaces compared to fixed sensors installed in the parking spaces.

Based on the mobility data they calculated that with 536 cabs in San Francisco downtown area, in 80% of cells, which mainly contained one road segment, the visit interval averaged in under ten minutes. This shows that even relatively small number of very active nodes can cover areas with high frequency. With cycling, the equivalent of cabs does not exist. However, if city has citybikes available for public usage, fitting those with sensors could approach cab like behavior where few nodes are actively used.

Commercial endeavors include crowdsourcing solutions too. City of Boston launched smart phone application that allows residents to report infrastructure issues, such as potholes [11]. By integrating the application with the other systems that are used by the city, reports would reach the responsible operator, who then could take steps to fix the problem. In 2014, the application was responsible for 28% of the city's service reports and had reached demographics that were traditionally not reporting about problems.

Waze is another example of smart phone application that crowdsources traffic information [65]. It navigation software that collects data both passively when application is kept open during drive and actively from user reports. GPS data is used to calculate for example average speed on routes and updating the road information. In addition, users can report about different things such as accidents, weather conditions and other factors affecting their route. The information is then used when calculating suitable routes for other users. Currently they advertise on their site having 100 million users.

Commercial solutions are also utilizing the embedded sensors in car. For example Here Hazard Warnings uses data from wipers, SRS (Supplemental Restraint System) airbags, ABS (Anti-lock Braking System) brakes and based on the available data can create different warnings [36]. These warnings can be for example about slippery road conditions or accidents, that are targeted to others drivers that can be affected. Data collection is not limited to specific brand of cars, as multiple car manufacturers can participate and share the data.

It is evident that vehicle related crowdsourcing has already drawn attention. Currently there is already available crowdsourced applications for cars, so it is plausible, that cycling will attract crowsourced applications too. Compared to bicycles, cars have the benefit of existing embedded sensors which can then be utilized for different applications. With bicycles, the lack of sensors must be solved.

2.3.2 Privacy and security issues when crowdsourcing cycling data

Crowdsourcing data comes with privacy and security issues for both sensor data provider and sensor data consumers, as described by Yang, Zhang, Ren and Shen [68]. They categorize the threats in three different main categories: Privacy threats, reliability threats and availability threats. As the mobile crowdsourcing networks they discuss have multiple different actors: the end users, the sensing crowd, the computing crowd and the service providers, these main categories have multiple subcategories where privacy or security could be affected in different ways for the different actors.

The threats that may realize depend on the crowdsourcing model. From BikeBox point of view the privacy threats and reliability threats that affect the sensing crowd and service providers are the most relevant ones and are further discussed in this section.

Considering first the privacy threats, Yang et al identify following cases: Privacy of the sensed data, privacy of computing inputs, privacy of the computing results, task privacy of end users and task privacy of participants[68]. Taking the view of BikeBox user, especially relevant here is the threat to privacy of sensed data. It refers to the situation where personal details of the sensor owner could be revealed through the data provided by the sensor, either by being straight out included to the data, for example GPS location or biometrics, or that further information, such as home or workplace locations can be deduced from any kind of data [68].

With BikeBox it's especially relevant to recognize the risk of revealing home or workplace locations or other routines as cyclist commonly start and end their trips to their home and frequently travel the same routes. Especially on less populous areas there is a risk that user's routes might be identifiable from data.

Reliability threat is the second main category by Yang at al and it's divided to three subcategories: Reliability of sensed data, reliability of computing results and reliability of transmission [68]. As the devices and sensors are owned by the sensor data provider, malicious tampering can be easily done and is hard to identify. Similar reasoning applies to the computing results too, though erroneous calculations might also result from honest misunderstandings.

These threats could manifest with cycling environment measurements too. If use cases focus on averages and long term trends, few malicious users among many have only very limited possibilities to affect the results. However, on less populous areas with only few data providers, malicious user might have effect on the outcome. If data is then used as decision support, it might direct resources to less necessary endeavors.

3. USE CASES AND REQUIREMENTS FOR BIKE-BOX

This chapter discusses about the three identified use cases, and the requirements for the prototype of BikeBox. Identified use cases and requirements affect the design of the prototype and testing of the prototype, which is why they are presented in detail.

3.1 Use cases

Three use cases were selected for this thesis: identifying different road qualities, identifying poorly lit areas and identifying slow parts and stopping points along the route. This section discusses about the motivations behind choosing each use case and possibilities such data could offer for both cyclists and the city. In addition, this section discusses the specific challenges the use cases cause to the data collection: Environmental objectives that are relatively slowly changing over time or over distance require less frequent measurement compared to those that undergo quick changes. In addition to the change, probability of unrepresentative measurement, even if correctly measured, should be considered.

3.1.1 Identifying different road qualities

The first use case is to identify different road qualities. As a muscle powered transport method, the quality of the route has perhaps even larger impact on the convenience of travel than with motoring. Smooth road makes easy cycling when rough surface makes pedaling harder and might even cause damage to the bicycle. For example sharp edged sand or rubble might break the tires. Especially crushed stones used to prevent slippery conditions during wintertime cause problems during spring, before the roads are cleared from the rubble [42].

The objective in this use case is to determine, if road surface quality can be evaluated from the measurements gathered from BikeBox. Road surface quality can be affected by various things: The original surface material can be asphalt, sand, gravel or for example tiles. The original surface material can be in good condition or be damaged by for example underlying tree roots, cracks or pot holes. The original construction might have undesirable features such as sharp pavement edges. There can be debris on top of the surface, good examples of this situation are the sanded roads after snow has melted but roads have not been cleaned yet.

The condition of the road is something that can vary a lot over distance as damage or rubble on road can be local so smooth road couple of meters away or even on one side of the path does not give the full picture. In addition, some features such as pavement edges impact only small areas. To gather comprehensive picture of the situation, multiple measurements should be acquired from the same route. Generally, the condition of the roads tends to change slowly over time. If the roads are regularly measured, the trend can give information about which routes deteriorate faster. However, it should be noted that loose rubble or sand on the road can cause sudden changes in the observed quality.

Information about the road qualities could be used for providing cyclists with more pleasant routes to ride. From the city's perspective, being able to observe up-to-date information about road qualities and route usages makes it possible to direct maintenance efforts first for the commonly used roads, where low quality affects many road users. Maintenance might include fixing deteriorated surfaces or sweeping loose rubble away.

3.1.2 Identifying poorly lit areas

Second use case is identifying poorly lit areas and recognizing broken street lights. Identifying poorly lit areas benefits both cyclists and pedestrians. While cyclists should be using lamps during dark for visibility reasons, poorly lit areas are considered to be intimidating by some road users. That may keep them from moving on certain areas after sunset, limiting what kind of services they use, transportation methods they choose and what kind of professional or recreational activities they partake. Darkness also makes it harder to assess road quality, which might cause cyclists or pedestrians from not noticing potholes or other hazards on the road. On areas that have both motored traffic and pedestrians and cyclists, lack of light may cause accidents because visibility is affected. Object is to find out, if poorly lit areas or possibly broken street lights can be identified from the gathered data.

Light conditions vary naturally during day-night cycles, and are affected by time of year. For cycling environment measuring, the focus is on artificial lighting, which can be influenced by city planning and maintenance. This sets requirements on when the data must be measured. If one area is entirely poorly lighted, that can be considered changing very slowly over time as it improves only with targeted investment. These are less local issues than road conditions, so less comprehensive measurements can give useful information. Well lighted areas on the other hand can start deteriorating by losing lights one by one. Identifying such points requires more precise measuring compared to general lighting situation.

The information gathered could be used to direct maintenance and further improvements on the areas that need it most. With long therm data, broken streetlights could be recognized from just poorly lit areas by comparing current and historical data from the same location. Cyclists that prefer well lit areas could again choose more pleasant routes for them.

3.1.3 Identifying slow parts and stopping points

Third use case is to identify slow parts and stopping points on the route. Cycling is often used as travel method over relatively short distances, for example within a city district or between them. Compared to walking it offers reasonable speeds, making it competitor for cars and public transport, even if the cyclists are exposed to the elements and must exert themselves.

However, if the speed of the travel is compromised, the attractiveness of the method suffers. If the cycling path is to follow same route than pedestrian ways, delays such as traffic light stops over same distance cause proportionally longer wait for cyclists than for pedestrians. For example, assuming speed of 15 km/h for cyclists and 5 km/h walking speed over 5 km route that has five minute long stops because of traffic lights, the delay from waiting causes 25% increase in travel time for the cyclist but only 8,3% increase for the walker. That example does not take into account the effects from mounting and dismounting required for cyclist to stop. Finding and also planning routes that offer as uninterrupted travel as possible, is a way to increase the convenience of the travel. In addition, if in future bicycle will be notable delivery tool, planning optimal routes has a financial need.

Slowness along the route might not always be caused by stops and waits. Other factors such as uphills, overcrowding and road qualities may affect the average speed too. Identifying the cause of the slowness is out of the scope of this work as that would likely require large amounts of long term data.

Stopping points and slow areas are time and location dependent as traffic situations can significantly vary between different times and places. Accurate predictions require long term data from large crowds as personal driving preferences can affect individual source. In addition, accidents can cause stops or delays on otherwise well flowing road.

The information gathered could be used to identify problems with road network planning, which can then be used to avoid similar structures in future and to fix current problems. Cyclists can choose faster and less interrupted routes to make the travel more convenient. Data could also be used to create navigation services that would direct part of the cyclists to use alternative routes if possible, reducing congestion.

3.2 Requirements for BikeBox

This section describes the identified requirements for the BikeBox-prototype. This includes physical requirements, battery life and power requirements, connectivity requirements, sensing requirements and security requirements. It is also noted when requirements for final product would differ drastically from the requirements for the prototype.

3.2.1 Physical requirements

The prototype has three physical requirements:

- Separate device that can be obtained independently from the bicycle and does not assume built in sensors. This is to avoid forcing the cyclists to choose specific bicycle manufacturers.
- It can be firmly attached to either body or rack of the bicycle. Bicycles can be used in rough terrain so safely securing the device is necessary. In addition, uncontrolled movements can introduce errors in the data.
- Sturdy enough connections and structure to stand driving on different roads an withstand bumps.

A usable product would have following additional physical requirements:

- Small enough size that it does not add unnecessary weight or drag for the cyclists and if the device is removed between drives, it should be convenient to carry along.
- Either easily mountable and removable or securely attached against theft. Bicycless are often stored in unlocked areas where theft can occur.
- Weatherproof in cycling weather, which includes rain, snow and sub-zero temperatures. Environmental data gathering should not be limited only to fair weather.

For prototyping purposes the small size and theft or weather related features were not necessary as test drives can be planned for relatively fair weather and on times when the device can be taken in secure premises after test drives.

3.2.2 Battery life and power requirements

For prototype the battery life requirements can be lighter than with usable product. Prototype must be able to do several test drives without recharging. Usable product must be easily rechargeable. For the convenience of the cyclist, usable product should not be required recharging after every drive, preferably allowing cyclist to recharge only rarely.

3.2.3 Connectivity requirements

Connectivity is central feature for both prototype and the usable product. Following requirements were identified regarding the connectivity:

- Wireless communication. As bicycles are moving around, wireless connection is only possibility for gathering real time data. Usability-wise, forcing cyclists to upload data manually after every drive would likely result in reduced amount of users and data.
- Connection must be available both inside and outside city limits. It must not depend on having inhabited buildings in near proximity. However, connectivity in very remote areas is not required. Cycling can be done between city districts and other sparsely inhabited areas, yet data is required from those areas too.

- Transmission packet size and speed must be enough to support data amounts generated by the device so that data can be fully transmitted during the drive instead of requiring full data transfer or even waiting period after the drive has ended.

3.2.4 Sensing requirements

The measurement data requires location coordinates. That can be provided by a GPS module. As the prototype set out to find what kind of environmental factors could be measured, sensing requirements were based on available sensors.

3.2.5 Other requirements

Even though security and privacy was not in the focus of the prototype, a BikeBox type of device generates sensitive data from the user. Gathering and using this kind of data from cyclists sets requirements on privacy and security. Published data should not reveal sensitive information from individual cyclists.

4. TECHNICAL DECISIONS BASED ON THE REQUIREMENTS

This chapter discusses about the necessary technical design choices based on the requirement presented in section 3.2. First, different available communication methods are presented: cellular networks, wireless local area networks and personal area network solutions, and their possibilties and limitations for BikeBox are discussed in Section 4.3. In addition this chapter discusses about the limitations of GPS positioning and possibilities of sensoring available in the BikeBox.

4.1 Communication options for IoT on the move

This section discusses the role of different communication solutions with Internet of Things. As the "things", or the devices in the Internet of Things is heterogeneous group of appliances from sensors and actuators in industrial environment to smart phones, the hardware and communication technologies vary from device to device. The mobility of cyclists causes challenges for the communication of the IoT device. Cyclists can visit urban city areas, outskirts of the city or city districts, rural areas and forest trails, even during the same drive. Devices should be reasonably sized and cannot be wired so they either depend on battery as a power source or on the power generated by cycling. These mean that connectivity must be available on very different areas and energy consumption must allow for reasonable battery life.

4.1.1 Cellular networks

Cellular networks include technologies over different generations such as GSM (Global System for Mobile Communications) from 2nd generation, UMTS (Universal Mobile Telecommunication System), EDGE (Enhanced Data rates for GSM Evolution) and HSDPA (High-Speed Downlink Packet Access) from 3rd generation and LTE (Long Term Evolution) and WIMAX (Worldwide Interoperability for Microwave Access) from 4th generation [61]. Cellular networks have significant benefit of coverage and range compared to either wireless local area networks or wireless personal area networks. However, the energy consumption has been challenge for the resource constrained IoT devices.

NarrowBand IoT (NB-IoT) is recent addition to the 4th generation LTE and it is specifically intended to support IoT solutions [50]. NB-IoT uses narrower bandwidths of 180kHz compared to the LTE which allows it to support ultra-low-complexity devices. In addition, to better support IoT usage, cells must be able to handle large amount of low throughput devices and energy efficiency must be improved to allow for longer battery lives. Other objectives for the NB-IoT were better indoor coverage and 10 second or less exception report latency.

4.1.2 WLAN

For the purposes of this work, Wireless local area network (WLAN) is used to refer to wireless communication technologies defined by IEEE 802.11 specifications. WLAN is widely supported by consumer electronics, such as mobile phones, tablets and laptops, as a method to create wireless Internet connection.

Compared on other technologies in this section, WLAN is outsider in the sense that the evolution of 802.11-standards has concentrated heavily on increasing the data rates with little regard on the power consumption [58]. However, to better support low power IoT solutions, new amendment 802.11 AH was introduced to the standard, with requirements that benefit resource constrained IoT world [5]. As with the NarrowBand IoT, one of the challenges that IoT context brings is the sheer amount of devices. Thus one of the new features in 802.11 AH is to require access point to be able to support up to 8191 devices. In addition, the amount of devices calls for cost effective solution. Operating under 1 GHz band allows for longer range, up to 1km, which compared to the personal area network solutions such as Bluetooth and ZigBee that function on 2.4GHz band, is longer. Differing from more traditional usage of Wi-Fi, IoT environment tends to utilize shorter data transmissions that may be sent infrequently. Accomplishing that is also necessary, and thus feature for the 802.11 AH.

4.1.3 WPAN

The different versions and generations of the Wireless Personal Area Network (WPAN) radio modules have varying characteristics regarding the features such as range and supported topologies. However, the common feature is the relative short range from meters, or tens of meters to the high end of several hundred of meters with line of sight. Bluetooth and IEEE 802.15.4 standard based technologies such as ZigBee are commonly known WPAN protocols implemented by different device manufacturers.

Bluetooth

Bluetooth as wireless, low power short range communication technology is commonly used as wireless option instead of cables for connecting for example peripherals such as keyboards or speakers to devices [30]. However, the use cases are not limited to that, and Bluetooth has different forms with optional extensions to use in varying situations. Both traditional Bluetooth, also called Basic Rate (BR) and Bluetooth Low Energy (LE) operate on 2.4 GHz band with one megasymbol per second rate, which, depending on the used codings, supports bit rates from 500kbit/s to even 3Mb/s. Bluetooth LE is more suitable for IoT environment due to the lower resource requirements, including smaller current consumption and implementation size.

BR operates by having a master device that provides the common clock and frequency hopping pattern for the slaves, that are synchronized to the clock and the pattern[30]. LE uses less physical channels than BE, 37 data and secondary advertising channels and three primary advertising channels compared to the 79 channels BE uses [28]. LE uses Time Division Multiple Access (TDMA) to save energy. The LE master allocates times when the slaves need to listen, allowing them to sleep outside the time slot.

IEEE 802.15.4 and Zigbee

IEEE 802.15.4 is standard for physical and media access on wireless, personal area networks and it supports both star and peer to peer topologies [38]. With star topology, network has a PAN coordinator and other devices in the same PAN communicate with the coordinator. Unlike coordinator, basic devices can usually sleep when not sending data. With peer to peer topology devices can communicate with each other and thus are able to form more complex networks, with multihop possibilities.

Zigbee implements its own network and application layers on top of the IEEE 802.15.4 radio standard. Current Zigbee 3.0, which is built on Zigbee PRO, has mesh networking with routing capable coordinator, routers, end devices and Zigbee Green Power Devices [71] [70]. Data rate can be 250Kbits per second, on 2.4GHz band with 16 2MHz channels.

4.1.4 Energy consumption differences between Bluetooth Low Energy and ZigBee, Wifi and 3G

Siekkinen et al presented energy utility ranges for both Bluetooth Low Energy and Zigbee 802.15.4, more detailed measurement setup is described in [55]. With Bluetooth Low Energy slave on single connection event, the energy utility depended of the application protocol data unit amount and connection event parameters. Using as an example a connection event with four packets in event and throughput of 10KB/s, the energy utility for Bluetooth LE was around 530 KB/J. On same paper they present measurements for Zigbee 802.15.4, which has lower energy utility of 300KB/J when throughput is around 10KB/s.

To compare these with 802.11g wireless LAN we can see that the energy utility of that is even lower than either Bluetooth LE or Zigbee 802.15.4. From Xiao et al, while the WLAN's energy utility is better with higher throughput, even with rate of 256KB/s the energy utility is less than 250KB/J, and slower rates have even worse, with 96KB/s one get only bit over 100KB/J [67].

Using Huang et al's measurements from cellular network's power characteristics, a sample of possible energy utility value for 3G network when doing bulk data transfer of 100kB would be around 20KBytes/Joule for 3G uplink, or even less [37]. For LTE uplink the energy utility could be around 50 KBytes/J for the same 100kB bulk data transfer.

While especially the cellular network values are directional at best and not as strictly comparable with the Bluetooth LE, Zigbee and wifi measurements, they do give some idea of what kind of energy consumption differences these connection methods have.

4.2 Communication between IoT-devices

Machine to machine communication with BikeBox type of solution could allow the devices to, for example, share real time environmental information with nearby BikeBoxes or manage measuring responsibilities withing group of bicycles that are traveling on the same route at the same time. Machine to machine communication and device management require protocols that can function in environment where resources such as network bandwidth, memory or disk space are limited. Examples of such protocols are Message Queue Telemetry Transport (MQTT)[8], Constrained Application Protocol (CoAP)[10] and Open Mobile Alliance Lightweight machine to machine (OMA LWM2M)[66], which are shortly described in following paragraphs.

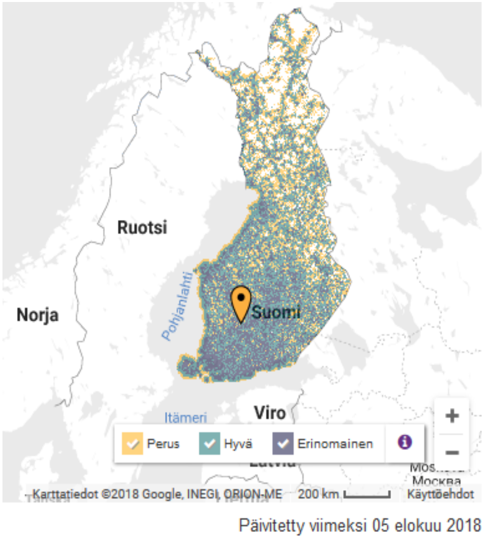
MQTT is protocol in resource limited environment [8]. It is not meant to be used as stand alone protocol but requires underlying protocols such as TCP/IP that takes care of the connection requirements: messages must arrive in order, packets mus not be lost and connection has to be bidirectional. MQTT follows publish/subscribe model and the network is built from clients and a server. Client might either publish new data or subscribe to receive data it is interested in. Server is a broker between the clients, forwarding the data from publishers to the subscribers. MQTT supports simple three level quality of service to determine if messages are delivered on best effort level, requiring arrival but allowing duplicates or requiring arrival without duplicates.

CoAP uses request-response pattern and it is designed to allow low resource devices to integrate with the web [10]. While it has similarities with HTTP, in addition of being more concise, CoAP is geared towards resource limited machine to machine communication: it has support for multicast and automatic discovery of resources. Unlike MQTT, CoAP functions over UDP and does not have strict connection requirements from the underlying protocol.

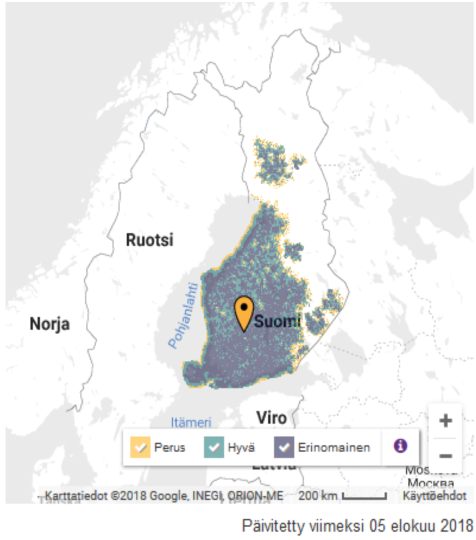
OMA LWM2M protocol provides device management functionalities for different machine to machine networks [66]. It is commonly used on top of the CoAP. The LWM2M Enabler consists of LWM2M Client and LWM2M Server. Protocol offers bootstrapping, client registration, device management and service enablement and information reporting.

4.3 Communication choices for the BikeBox

From BikeBox point of view, cellular networks offer good coverage in both urban and rural area. While coverage depends on the country, for example in Finland NarrowBand IoT is



(a) Coverage of 3G and 4G in Finland by Telia



(b) Coverage of NarrowBand IoT by Telia

available in more populated areas, and 3G or 4G are available in all but the very remote areas, as seen from the pictures 2b and 2a, which show the coverages in Finland by operator Telia [59]. The 3G and 4G suffer from the energy inefficiency, however NarrowBand IoT has made improvements on that area. One drawback for the cellular network solutions is that they require separate subscription and SIM card for the connectivity unless dual-SIM or multi-SIM solutions are available for the customer. That can cause additional charges for the user.

Open wireless LANs are commonly available on urban areas, but scarcer in outskirts, rural areas and off-tracks. If the device is very memory limited, on-off connections can cause loss of data. Security concerns such as someone capturing the data for transmitting the measurements over open wireless LANs cannot be ignored either.

Wireless PANs have two possibilities with BikeBox. Point to point connection can be used to connect the BikeBox to smart phone and data is transmitted to the phone and either stored temporarily there and transmitted forward later or transmitted in real time with what ever communication option the smart phone has available. This allows using energy efficient, short range technologies on the BikeBox, but requires user to have suitable smart phone and to carry it with them on their cycling trips.

Second option is that the BikeBoxes form a mesh transmitting data over other BikeBoxes in the area. In addition gateway infrastructure is required. While theoretically possible, the additional infrastructure requirement and requirement for enough nearby BikeBoxes can make this option impractical.

3G connection fulfills the connectivity requirements: It's wireless and connection is available with enough speed and packet size, which ended up being the deciding factors. For the prototyping purposes, the energy consumption didn't cause problems, though for usable product more energy efficient connection would be better. At the time when the prototype was built, NarrowBand IoT network was not yet available.

Other considered connectivity options lack the coverage. While there are open WLAN networks available in the cities, as can been seen from Figure 3, the hotspots clearly do not offer full coverage, especially between city districts.

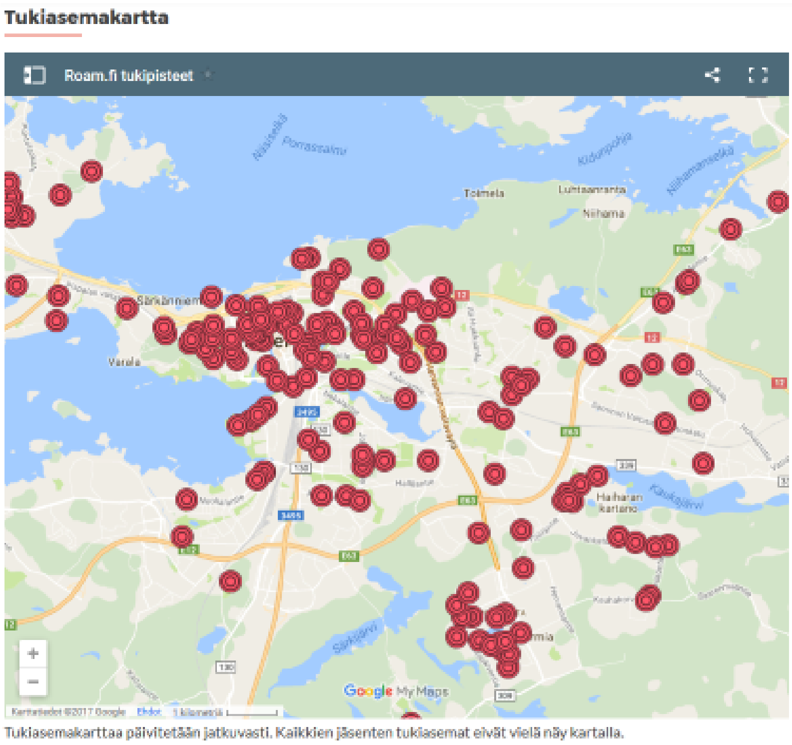


Figure 3. *Wlan hotspots from roam.fi represented by red circles in Tampere region.*

In the prototyping phase, using Zigbees or similar personal area radio modules would have required multiple devices or infrastructure that does not exist in place already to collect the data nearly real time. Without those, the situation would have been nearly akin to just saving the data on the device and transferring it by any wireless or wired method after the drive.

Compared to Zigbees and other such smaller range radio modules, both cellular, and Wifi networks benefited from having existing infrastructure which allows Internet connection without building separate gateways or other networking features for the prototype. For the same reason, machine to machine features were left out of consideration in the prototyping stage.

Bluetooth connection is readily available in smart phones, so it could be used to transfer data from BikeBox to smart phone and then from smart phone to server using 3G connection. This would allow for cheaper radio modules in prototype but would add extra step and require separate software on smart phone side. For that reason Bluetooth was not chosen in prototyping stage and the BikeBox was connected with its own 3G radio module. In commercial product Bluetooth could be feasible option, especially if smart phone application offers additional services for the cyclists. Downside is that application and data transfer will use the battery of the smart phone, which might lead to user lacking power in their phone for other necessary things over the day.

4.4 Location for IoT on the move

As with the communication, the location must be available wherever the cyclists drives. That excludes for example WLAN-based positioning that relies on available WLAN-hotspots. Satellite based Global Positioning System (GPS) is used as a source for location in several fields of study. The accuracy of GPS position is usually in order of 10m, for consumer grade modules [7]. However it is affected by several factors, including the satellites available, the receiver itself and how the signal propagates. Schipperijn et al study how GPS accuracy is affected by the different urban environment, by data collecting rates and by different transportation methods [51].

They classify the environment as open, half-open or urban canyon, depending if there are no buildings, buildings on one side or buildings on both sides within 25m range to the route [51]. They measured the accuracy of GPS position over four different routes, and tests for cyclists were done on bicycle lanes. Following results are combined from all of the routes. In open areas for cycling the amount of data points within 10m from the lane was 90.1%-92.3%, depending on how often the GPS measurement was taken. For 5 second interval it was 91.7% and 38.7% of data points were within lanes. In half-open areas for cycling with 5 second interval, 25.7% of data points were within lane, and 92.5% were within 10 meters. In urban canyons the accuracy is most affected, with 5 second interval only 13.2% of data points were within the lane and 76.4% within ten meters of the lane.

Based on the accuracy results from Schipperijn et al, it's clear that perfect accuracy cannot be expected from the location that the GPS provides. Pinpointing exact locations may prove difficult, however identifying general status of the road should not be affected that much as long as there is no risk to confusion which roads or routes the received results match to. If the accuracy proves to be problematic there are methods to consider for improving the accuracy. Inertia Measurement Unit (IMU) used in combination with GPS to could be used to improve the positioning [69] [23]. Map matching, where the knowledge about road network is used to match the location to the road, could be used when not off-road cycling [12].

4.5 Sensoring the BikeBox

This section discusses the sensors available in BikeBox and the possible use cases.

4.5.1 Accelerometers

Accelerometers are sensors that can measure acceleration, vibration, shock and tilt [19]. The unit for measurement is g, which represents the effect of gravity. One g equals to $9.81 m/s^2$, so with for example stationary three axis accelerometer, the axis orthogonal to the ground will measure 1g, and the axes parallel to the ground will measure 0g. When moving, the sensor measures the acceleration on each axis, caused by the movement the sensor experiences.

While considering the possible applications from the accelerometer data for cycling environment, one option would have been to use it for the tilt of the bicycle, to notice for example uphill or downhill driving. However, quite often the topography of the cities and nearby regions are already well known, so using cyclists to measure it does not yield much new information.

Second option could be accidents and falls. Using the accelerometer to try to measure when a bicycle has fallen or experienced acute shock, one could attempt to locate areas where cyclists are experiencing more accidents. If such areas would be known, the traffic planning of the area could be improved to mitigate the risks. In addition, having the knowledge of such areas could change human behavior, improving safety by making people more careful. While this could have brought important new information, safe testing method was an issue.

Third possibility is trying to measure the vibration, jolts and shocks that the bicycle is experiencing from driving on uneven terrain. Recognizing different levels of vibration caused could be used to identify how rough or smooth the road is. This could be used to argue about the quality of the road, which then could be used to inform cyclists about better quality road options and target maintenance to the roads with poor quality. This was chosen as the approach for this thesis, because it yields information that is not currently widely available and testing does not involve high risks.

4.5.2 Light sensors

Light dependent sensors can be used to measure the intensity of the light [27]. The sensor available in BikeBox is based on photoresistor, which exhibits increasing resistance when the light intensity is low.

While light dependent sensors could be used in bicycle for controlling cyclists light, that does not collect environmental information about the cycling. However, the ambient light is environmental factor that can be collected. The natural light changes that are caused by the day-night cycle are not that interesting from the point of view of cyclists, as those are well documented and outside of human interference. Artificial lightning on the other hand is human controlled and part of the city infrastructure. Collecting data during times of day that rely on artificial lightning could be used to map areas that have high or low light intensity. From that kind of information one could identify the areas that are poorly lit.

4.5.3 Dust sensors

Optical dust sensors measure the amount of dust particles in the air by detecting light that is reflected from the particles [29]. Such sensors could be used to analyze which areas suffer from excessive amounts of particulates in air. For example what is the air quality like during winter, when studded tires break particulates from road surface or during spring when residual sanding creates dust as the street dry.

5. PROTOTYPE

The technical part of this work consists of prototype for a device that measures environmental characteristics, such as ambient lighting, for a cyclists. A prototype was built with pre-existing components, which are described in this section. Arduino UNO was chosen as the microcontroller because it was easily available and can be expanded with various peripherals [6]. Figure 4 shows the hardware components and their connections. Figures 5a and 5b show the prototype without and with the casing.

As the prototype requirements asked for sturdy connections to withstand bumpy ride, the Grove system by Seeedstudio was chosen for attaching the sensors [53]. Grove system offers standard 4 pin interfaces to connect different modules, like the sensors, to the project. Grove Base Shield is attached on top of the Arduino UNO and sensors are attached to the Base Shield, which has four analog, seven digital, one Universal Asynchronous Receiver/Transmitter (UART) and four Inter-Integrated Circuit (I2C) interfaces. While soldering can create sturdy connections too, the Grove system has the benefit of easy detaching if sensors needs to be changed during prototyping.

For data transfer purposes, 3G and GPS shield [3] for Arduino was chosen. It uses SIM5218E module that supports UMTS/HSPA mobile communication technologies and GPS positioning. It also offers UART interface, which was used for communication between Arduino and the shield.[56] Shield was easily available, though relatively expensive solution. For the prototyping purposes, the energy consumption didn't cause problems, though for usable product more energy efficient connection would be better. It was also considered positive side that the shield could handle both data transmission and GPS positioning.

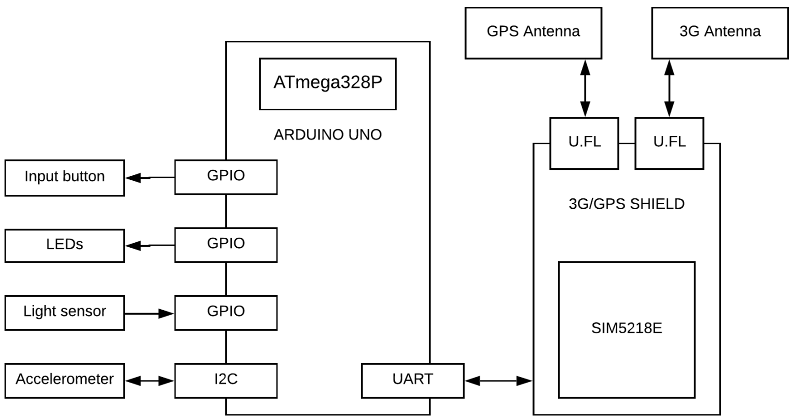
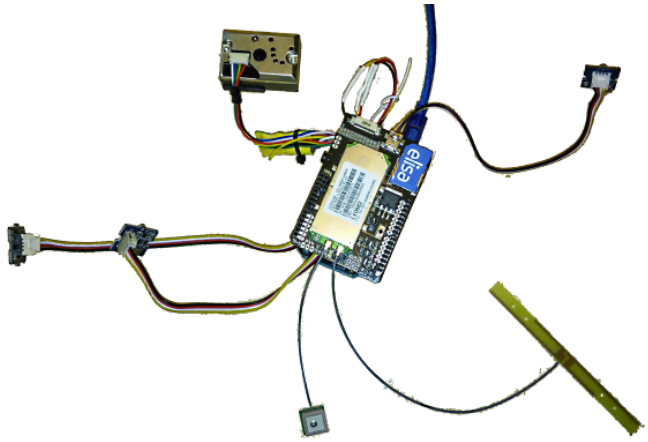
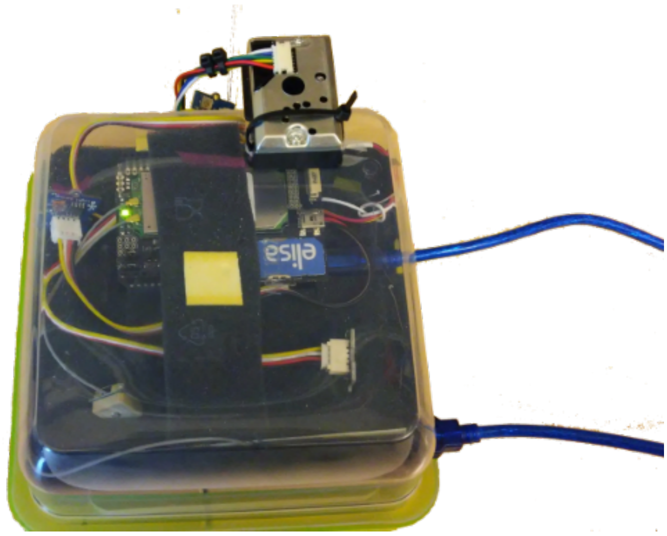


Figure 4. *Block diagram of the prototype architecture.*



(a) *Prototype without casing*



(b) *Prototype with casing*

Prototype was powered with a power bank as they are easily available in reasonable physical sizes and long battery life. The 3G shield required two ampere peak currents, which is also possible to match with a power bank. While battery life optimization was not in the scope of this work, it was tested that the device could work continuously for around 12 hours with 12000mAh power bank.

The electronics were packed in plastic container and fitted in foam rubber to disallow uncontrolled movement around the box. Accelerometer was positioned in slot cut to the foam rubber to keep the axis orthogonal to the ground consistent during the drives. Powering the prototype was possible by attaching the USB cable to the power bank, also inside the plastic container. A button was added to allow changing between software modes if necessary, and two Light Emitting Diodes (LED) where added to notify tester about software mode and if the GPS is receiving data properly.

5.1 Sensors in prototype

Grove Light Sensor

Grove Light sensor measures ambient light while cycling. It is analog sensor using light dependent resistor, also known as photoresistor. With photoresistor the resistance grows when it's dark. Response time is 20-30ms and supply current 0.5-3mA.[31] [27]

Grove 3-Axis Digital Accelerometer $\pm 16g$

Grove 3-Axis Digital Accelerometer measures proper acceleration with maximum range being between -16g and +16g, detecting inclinations under $1\circ$, User who excepts smaller accelerations can use narrower range for better accuracy. Supply current for the accelerometer is typically 140μA or less depending on the output data rate, standby mode, depending on the voltage, can be 0.1μA. It has I2C and SPI interfaces available. [1] [18]

Sharp GP2Y10 Compact optical Dust Sensor

Sharp GP2Y10 Compact Optical Dust Sensor is optical sensor that detects the reflected light from dust with phototransistor [29]. During testing phase this sensor was deemed unsuitable and no usable results were received from it. Possible reasons include too fine dust and good air quality outside to be registered with the sensor or technical issues with the sensor. It was removed from the prototype in the later test drives.

5.2 Data

For the data format of the prototype, comma separated value (CSV) format compatible with WSN OpenAPI Gateway (WOAG) [62] was chosen, which was clear and readable for prototyping purposes even if it will consume more resources than concise bit representation would take. Data was sent to server, which collected the data and stored it into CSV-file.

Data message sent from prototype, depending on measurements included, looks as follows. It includes information about the message type and version information on the first line. Each measurement follows on its own line, starting with timestamp. Timestamping was used in prototype slightly differently than the WOAG defines, the prototype used GPS timestamp as absolute time of the first measurement line in a package, which also includes the GPS location data. In the prototype, following measurement lines use relative timestamp as milliseconds passed from the GPS timestamp. The WOAG intended relative timestamp to indicate how far in the past the measurement was taken, as the message is passed over the network [62].

Relative times compared to GPS timestamp were used to allow possible interpolation of location for measurements that are included later in the same package but do not have their own GPS location. That can be used when measurement cycle is long and continuous polling for GPS location want to be avoided, and cyclist has moved significant distance before next GPS measurement.

Single measurement line includes in addition to the timestamp a network id, node id, sensor id, measurement name and values, which can be named and have unit. Multiple values on single measurement line were used when the same measurement contains multiple components, as with accelerometer. A packet could include multiple measurements from same sensor.

```
"SIDF:DATA,1.7,5,0,0
2015-12-08T07:22:36,1,1,4,GPS,N = 6126.825725,E = 02350.148771
+1,1,1,2,Light,4.01
+705,1,1,2,Light,4.01
+1411,1,1,1,Temperature,15.7 C
+1411,1,1,1,Pressure,1007.89 hPa"
```

Due to the Arduino's space limitations and overhead from the message type, different measurement cycles were used between test runs. All sensors were not active during all measurement drives. Used sensors affected the measurement cycle length and how much measurement lines were collected in the same package. However, to give scale, during most runs a package was sent every 1-5 seconds.

5.3 Location and timestamp

Same 3G and GPS shield that is responsible for the data transfer is used for GPS tracking during the drive. As Arduino does not have built in real time clock, the measurement time is taken from the GPS data, which gives current time in UTC. In addition, each measurement taken is stamped with the measurement's time difference from the received GPS time in milliseconds using Arduino's clock.

6. RESULTS

This chapter discusses about the results from the test drives done with the BikeBox and about the survey conducted over Internet to 97 cyclists.

6.1 Test drives

This section describes the test drive setups and observations from the test drives. During the testing phase, multiple test drives were done, but the results are discussed using example drives. To protect the privacy of test drivers, some of the test drive data may have been cut away to avoid revealing exact starting or stopping points.

6.1.1 Test drive setup and sensors

During testing phase different testing setups applied. Depending on measurement runs, sensor combination and measurement and data transfer frequencies were varied to find balance between sufficient amount of data and lack of internal memory and data sending frequency.

For the accelerometer the main measurement setup applied approximately as described in Table 1. Inconsistencies in data transfer time causes alteration in the burst intervals. The Grove 3 axis digital accelerometer used in prototype has maximum measurement range of $\pm 16g$ but it was used in $\pm 4g$ mode to achieve better accuracy on the relevant range.

Table 1. *Test drive setup for identifying sanded bicycle roads*

Sampling frequency for burst	30ms
Burst length	15 samples
Burst interval	1-4s

Measurements were collected in bursts of 15 separate accelerometer samples with approximately 30ms separation between each measurement, making the burst duration to be around 440ms. Each burst was joined with GPS location data which was requested right before starting the measurements. After all burst measurements were collected, data was sent to server over 3G connection. This contributes to the interval between bursts, as next burst is started after the transmission is finished.

Sent data package consists of GPS location row and accelerometer measurements. GPS location row includes time stamp, identifiers for node and measurement type in addition to latitude and longitude. Single accelerometer measurement row includes approximate time difference from the GPS location's time stamp in milliseconds, sensor identifiers and acceleration data from the axes x, y and z in g. The precision of acceleration data is given to four decimal places. Due to the position of sensor in the setup, the axis that sensor itself considers to be its x-axis is actually the axis that is orthogonal to the ground.

With all the accelerometer data, it should be noted, that in addition to the characteristics of the sensor and sampling setups, measured values may be affected by the physical features of the bicycle and the casing of the prototype. For example, size and pressure of the tires, possible suspension in the bicycle, total mass of the bicycle and driver and cycling speed may factor in how much of the jolts will be transmitted to the mounted sensor.

The test bicycles did not have any suspension, but did have different total mass and driving speed varied depending on driver and situation. The box containing prototype was tightly mounted on the pannier rack as shown in Figure 6.

Figure 6. *BikeBox mounted on the pannier rack of one of the test bicycles.*

For the photoresistors, the measurement setup varied more. Sampling frequency varied between 1 and 5 seconds. Sent data packages included the GPS location row as well as the light measurement rows, generally one GPS location per light measurement. To ease the interpretation of data from photoresistor, two graphs present the resistance data from three different light situations over the same basic route. The routes might have slight variation in the starting end ending points.

Figure 7 presents two drives from two different days in April in Tampere. Both drives were done in forenoon between 9 and 10, within few days from each other to minimize the difference in sun's position. The first drive was taken during very overcast day with slight rain of sleet. During second drive sun was mainly unobstructed even though some light cloud formations were present. The third drive, results presented in Figure 8, was measured during night, between 3 and 4, while the route was lighted by streetlights. The drive was made in opposite direction, but the order of data in the graph has been flipped to match the direction in Figure 7. However, the graphs should not be used to compare positional lightning differences but use it as a profile for the ranges of resistance values during different situations.

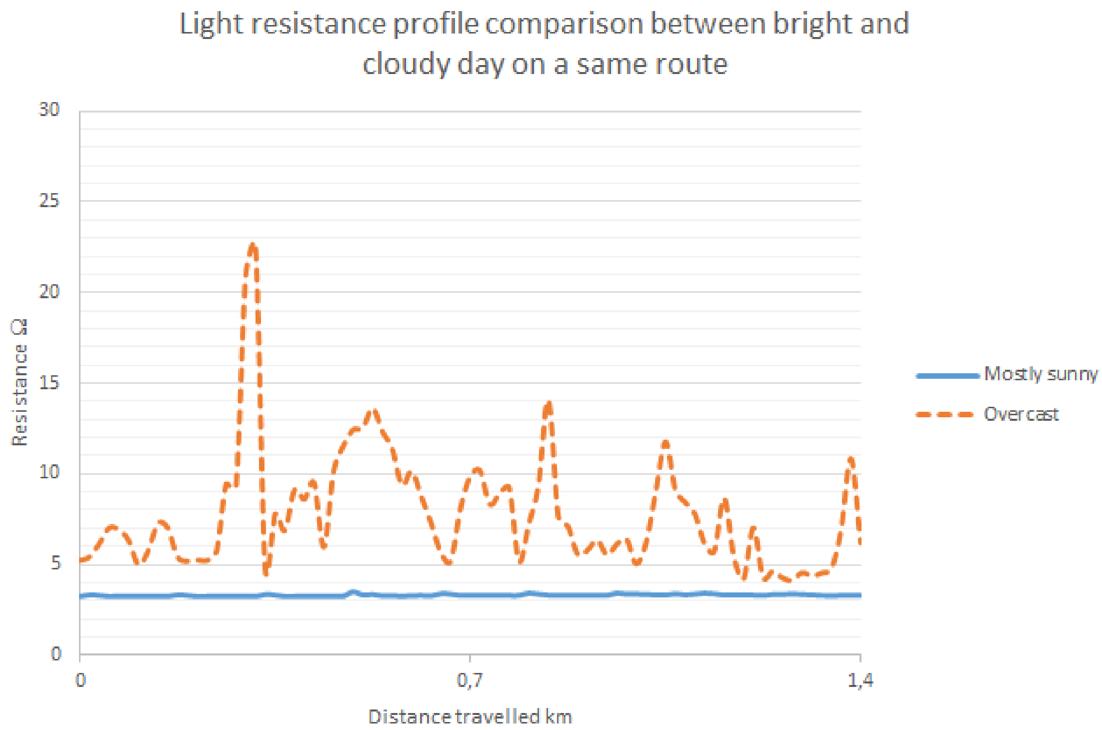


Figure 7. *Comparison profile from two drives, sunny and cloudy day, as reference for photoresistor behaviour.*

From the figures we can see that during the sunny drive the resistance stays quite steadily over 3 ohms. That is consistent with other measurements taken in bright daylight or under bright lights indoors. Variance is very low as the ambient brightness dominates the measurement environment. During overcast day the resistance varies more, and environmental factors such as shadows caused by trees or tall buildings affect the value noticeably. The night drive results are on different order of magnitude compared to daytime drives, which is why they are shown in separate graph.

6.1.2 Observations from the test drives

Main goal of this work was to find out if certain environmental characteristics can be observed from the measured data. In this chapter we present observations regarding the use cases presented in Chapter 3: Identifying different road types and qualities, identifying poorly lit areas and identifying slow parts and stopping points on the route. To preserve privacy of test drivers, some of the test drives have been pruned from the beginning or the

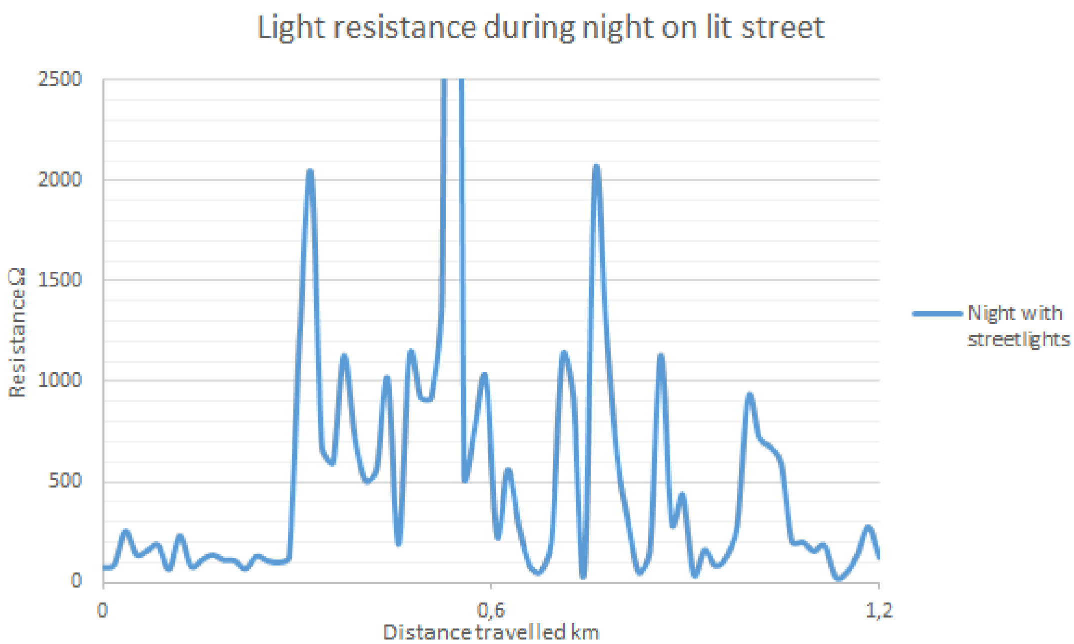


Figure 8. *Drive during night time with streetlights as reference for photoresistor behaviour.*

end to hide exact start- and endpoints.

Identifying different road types and qualities

In following visualizations a moving window variance is calculated from raw accelerometer x-axis (orthogonal to ground) data and mapped to location. Each location point on the map represents variance that is counted over 3 bursts: present one and two previous ones. That means the variance is counted over 45 separate measurements. The length of the window was approximated to keep the measurement's relevance to the location it will be mapped to while mitigating effects from outlier values.

With the prototype the variance was calculated on the server side, however, calculating the variance on the device and limiting sent data would be possible if raw data is not required for any purposes.

Figure 9 shows single drive variance results from example drive 1 mapped to the locations using GPSVisualizer [52]. The locations have not been compensated for any inaccuracies with GPS positioning, so some misplacement is clearly visible, especially near the lake's shore. A path or road was followed during the drive. This clearly does present a challenge for recognizing road qualities. If the GPS measurements are not precise enough, it can be difficult or even impossible to map it to correct road. Multiple sources of data could mitigate the problem.

In the figure, lighter blue colors represent low variance whereas dark blue and reddish colors represent higher variance, as shown in the legend. In addition, seven locations are marked with numbers 1-7 to indicate points, were noticeable changes happen in the route.

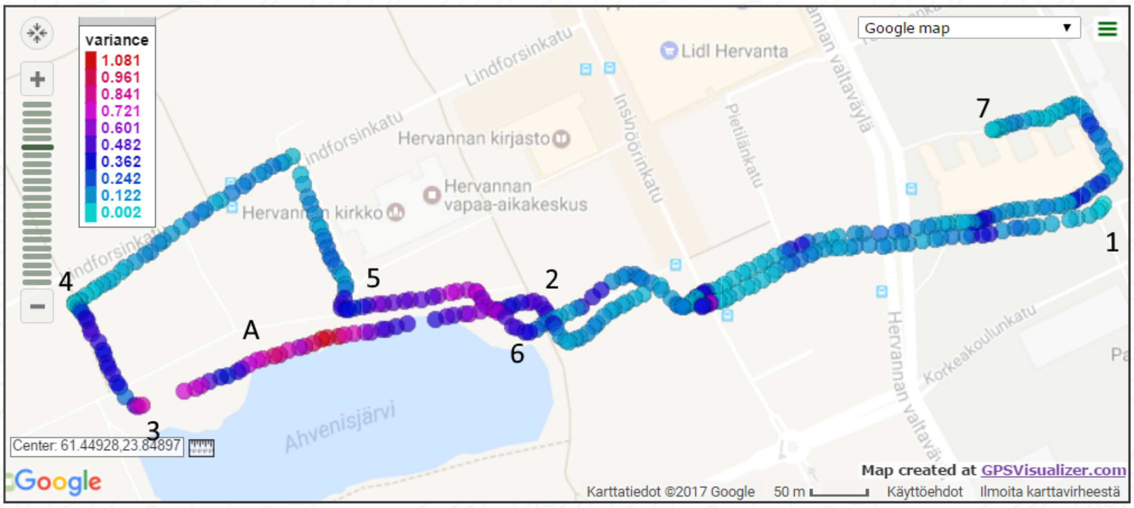


Figure 9. *Moving window variance mapped with GPS positions from example drive 1.*

While higher variances are observed in smaller patches all along the route, due to for example street crossings, the lakeside path, between locations 2 and as well as 5 and 6, shows longer period of exceptionally high variance. The physical realities of said location include heavy sanding residue from wintertime sandings on asphalt road. Figure 10a shows the sanded street near position A on the map 9.

Another notable area of continuous, high variance, is between locations 3 and 4, where the path took on sand road shown in Figure 10b. Table 2 shows average of the variances between each numerated location with description of road type. The differences between mainly asphalt, sanded roads and sand road are notable during this drive.

Table 2. *Average of variances over different parts of the route during example drive 1.*

1-2	Mainly asphalt	0.17
2-3	Heavily sanded asphalt	0.62
3-4	Sand road	0.29
4-5	Mainly asphalt, some paving	0.13
5-6	Heavily sanded asphalt	0.55
6-7	Mainly asphalt	0.17

On separate drive, example drive 2, on partially overlapping route, the same moving window variance calculations are mapped in Figure 11 and averages are presented in Table 3 with road type descriptions. During this drive, residue from winter sandings has been removed from the roads, which explains the drastic variance differences between the shore-side areas.

Identifying poorly lit areas

In Figure 12 photoresistor data from test case one is mapped using same GPSVisualizer as in previous chapter. The example drive 3 was done after sunset, while streetlights were on.

(a) Sanding situation at position A

(b) Sand road between positions 3 and 4

***Table 3.** Average of variances over different parts of the route during example drive 2*

1-2	Sand road	0.44
2-3	Asphalt	0.06
3-4	Sand road	0.37
4-5	Asphalt	0.11
5-6	Smooth paving	0.23
6-7	Mainly asphalt	0.14
7-8	Sand footpath with pits	0.45
8-9	Mainly asphalt	0.12

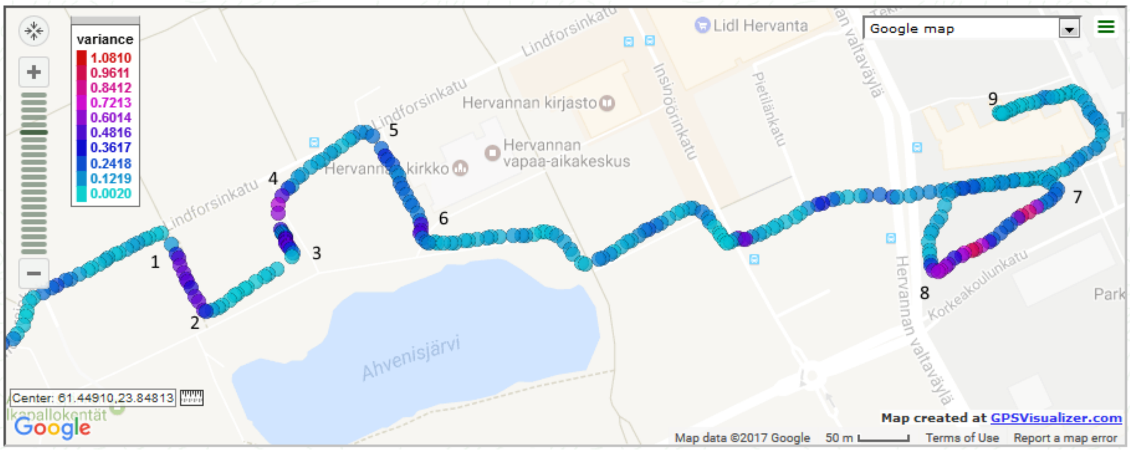


***Figure 11.** Moving window variance mapped with GPS positions form example drive 2.*

Photoresistor data during test drive ranged from 13 to 2547. However, in Figure 12 values above 1000 are visualized on the same level to reduce the effect of few outlier datapoints to the color range. With photoresistor it is important to note, that higher value means lower

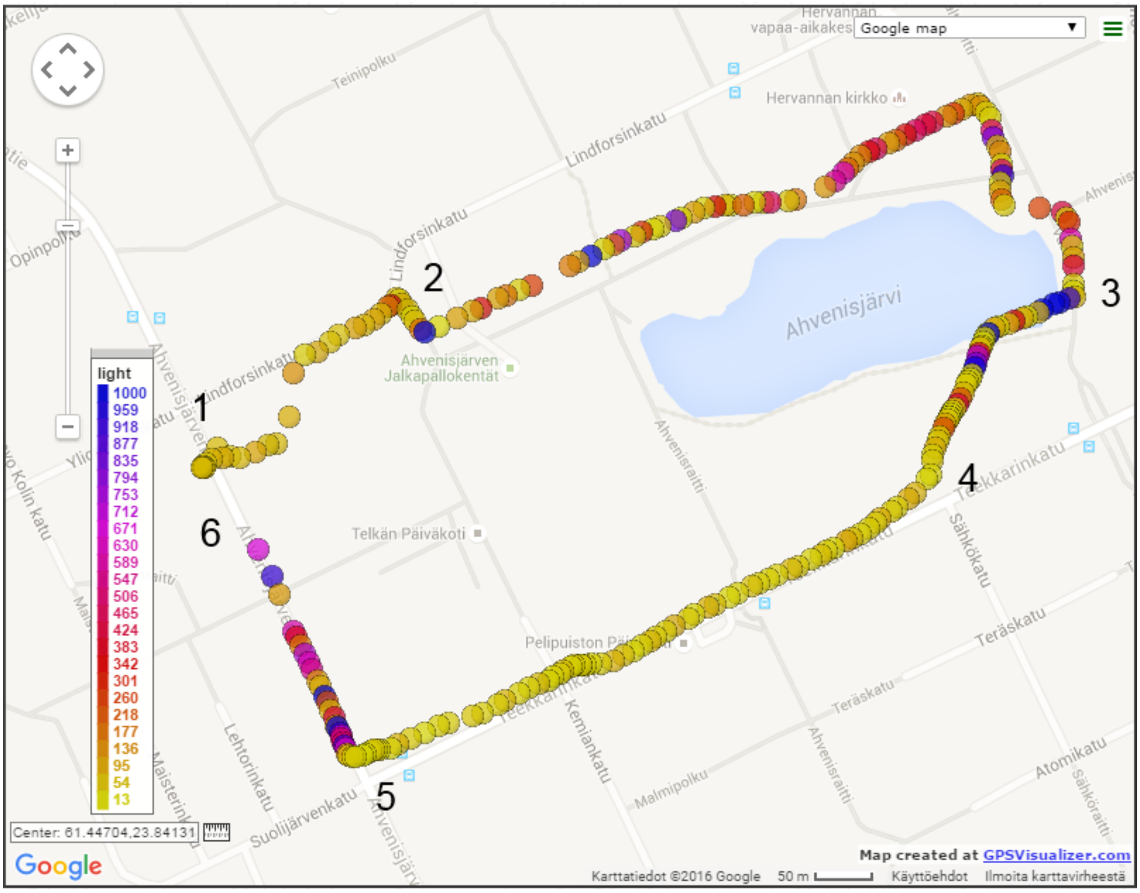


Figure 12. Photo resistor data from the example drive 3

lightning, and common ranges were discussed in Section 6.1.1. In visualization yellow color represents relatively bright lightning and as color changes towards dark blue the amount of light reduces.

In addition to the light information, six locations are numbered from 1-6 in figure 12. Between points 1 and 2 as well as 4 and 5 the drive took place in well lit area, next to unobstructed streetlights. The motor road between 4 and 5 has powerful streetlamps on both both sides, which light the sidewalk too. Area between 2 and 3 is walkway through parklike area surrounding the lake Ahvenisjärvi. Some parts of the walkway are surrounded with woodland. The route has streetlights, but they are smaller and dimmer than those lining motor roads.

From point 3 the measurement drive turns to small footpath in the forest. The area between 5 and 6 is showing us situation, where the motor road does have streetlamps. However, between sidewalk and motor road there are large trees planted, which block most of the light to the sidewalk's side.

Identifying slow parts and stopping points

As all of the gathered data packets includes GPS location, approximating speed and traveled distance between measuring points is possible. Figure 13 visualizes speed data from four separate morning commutes, later referred as example drive 4, taken approximately between 6:20 and 6:40, exact times depending on the day. Each drive takes almost same route each day. Speed data is calculated from two consecutive measurement points using the timestamps from GPS and taking their difference and distance between the GPS locations. Calculated speed is then joined with the latter location. In visualization 8m/s and above continue the maximum color scheme in legend, and 0.5m/s and below continue the minimum color scheme.

As we can see from the Figure 13, it is possible to identify slower parts on the route based on the speed values. Green values represent higher speeds and red values represent slower speeds. Comparing on the map locations, on this specific route, many of the slow parts correspond to intersections, where the cyclists must slow down or wait for lights or cars.

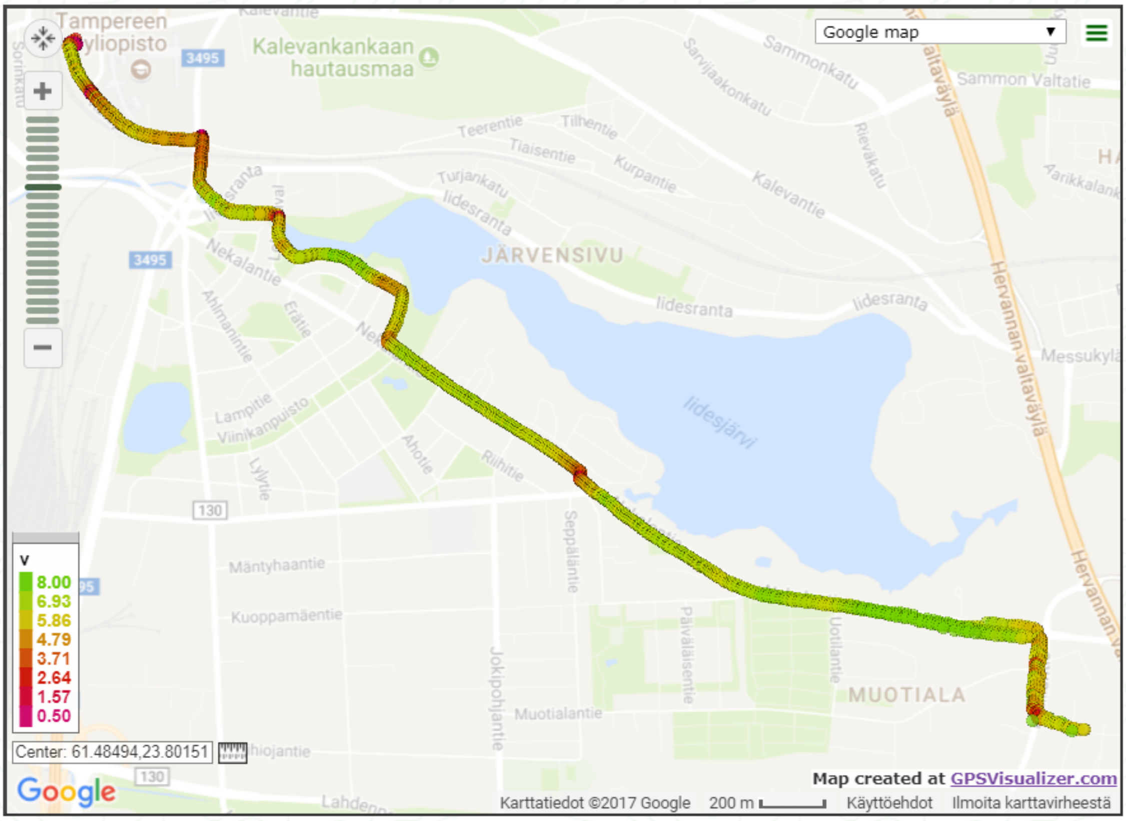


Figure 13. *Speed from four morning commutes (example drive 4).*

In the interest of finding out stopping points, the same four morning commute data was used to calculate sections where cyclist's speed dropped below one meter per second. One meter per second was used as the limit because GPS positioning is not perfectly accurate so two measurements taken while standing still can differ from each other, resulting in non-zero speed. The duration of each such section was calculated and mapped.

Figure 14 combines these delays with road quality data, giving example of map where different environmental factors could be shown for the cyclist. Delays are represented by the green circles, which were scaled larger based on how long the delay was. If same location had delays from multiple drives, those green circles were plotted on top of each other. In this example the largest circle corresponded to 57 second delay. Road quality was calculated with the same moving window variance as in earlier section.

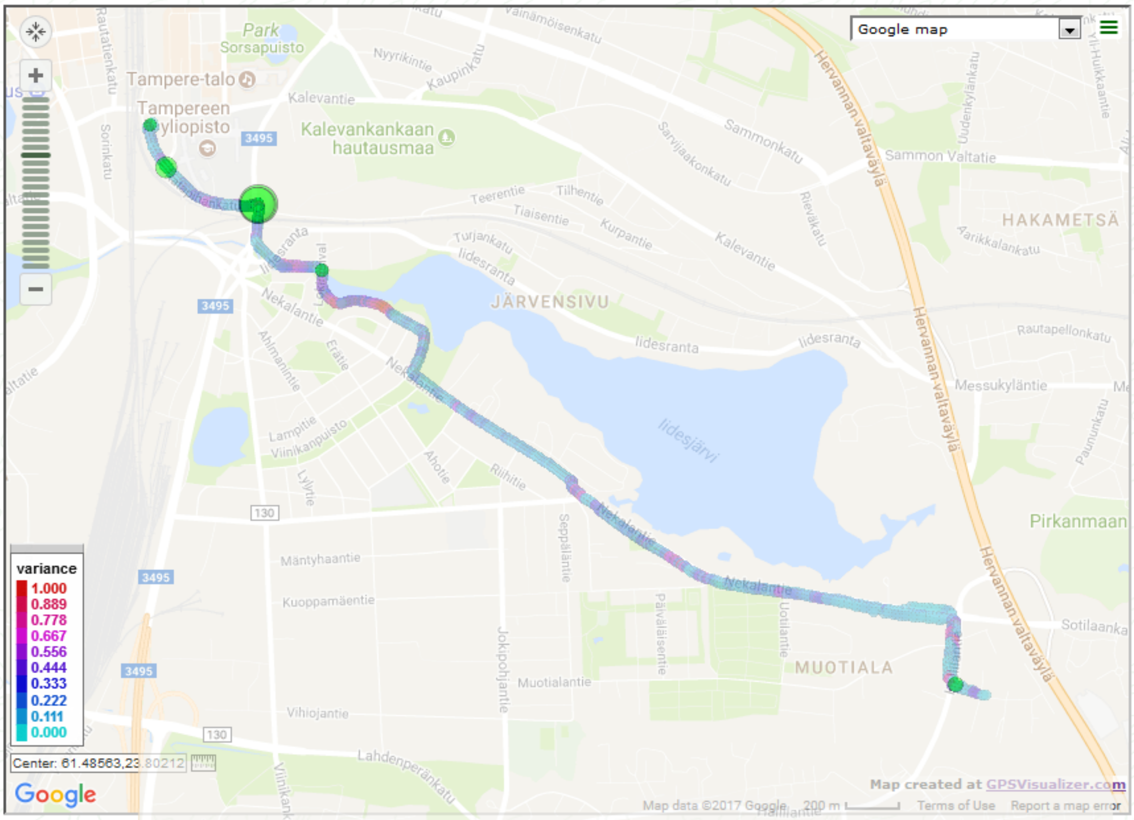


Figure 14. *A combined map for road quality and delay-causing locations (example drive 4).*

6.2 Survey

A survey was conducted to map what kind of elements or features in environment are considered to be hindering or beneficial for cyclists. It also questioned what kind of devices people are currently using during cycling or if they use any supporting devices at all.

The survey was carried out as Internet questionnaire. Answering was possible to anyone who got the link, which was distributed through social media. Amount of answers was 97. Majority of the answerers, 94%, belonged to the groups who cycle at least few times a week during their cycling season.

In following sections we discuss answers from the survey, first by giving background information about what kind of bicycling the participants do and then describing what kind of conditions they avoid and what they consider important in cycling routes. Current devices in use are also shortly discussed. Finally the feature and data suggestions for BikeBox-type of services are discussed.

6.2.1 Cycling motivation and environments

Given that cycling is versatile activity that can be used as transportation and physical exercise, we wanted to assess why and where answerers cycle. For that reason, we created categories for cycling styles and environments. Cycling style addresses motivation behind the cycling, and it was divided in three different categories: transport, sport and recreational.

Transport refers to situations where the main motivation for cycling is to get from one location to another. Commuting would be example of such situation. Sport-category is used when main focus of the activity was physical exercise. Third category, pleasure, is for situations where cycling might be done without clear destination, to pass time or find new places.

Categories for cycling environments depended on the chosen style. For transport, one could choose between short distances within city district, longer distances between city districts or cycling in dispersed settlements. Both sport and recreational cycling had four categories: Inside city districts or city center, in outskirts of city or city districts, in dispersed settlements or rural areas and forest trails or other cross country areas. As an additional option, bicycle touring was offered for those who do longer, possibly multi-day treks with bicycle.

In the survey, answerers could choose three to five options to best describe their cycling habits. Large majority chose both transport options, as 82,47% chose short, intra city travels and 84,54% chose longer, inter district travels. Sport cyclists preferred dispersed settlements or outskirt areas and recreational cyclists in-city areas. More precise distribution of cycling styles and environments is presented in Figure 15.

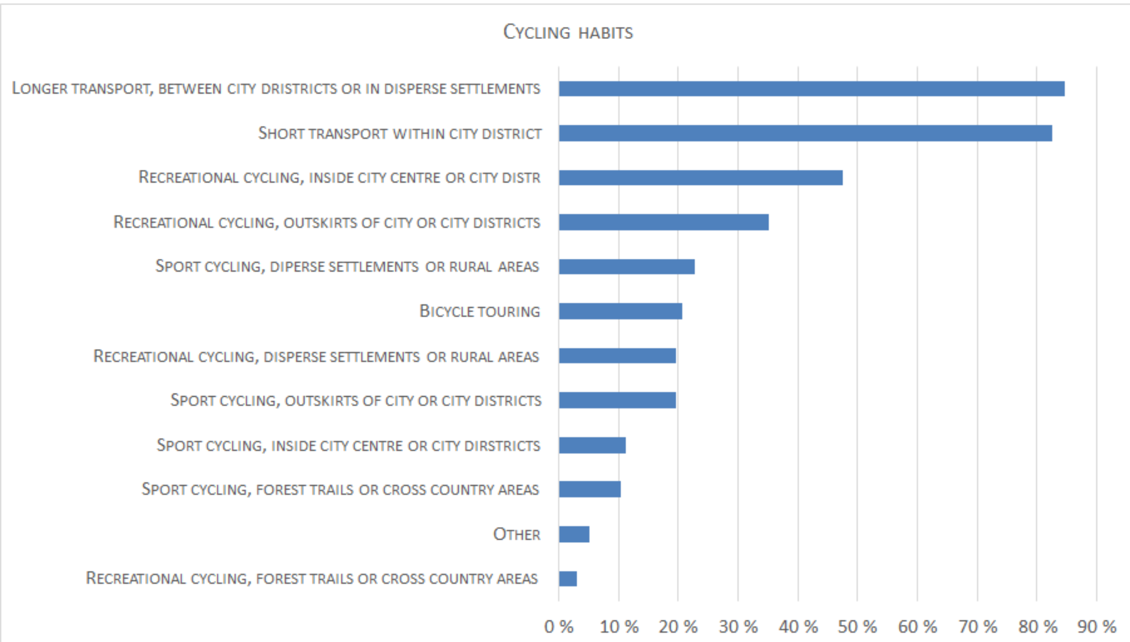


Figure 15. *Cycling habits. 3-5 best fitting options chosen from list by answerers.*

6.2.2 Cycling conditions

To gain understanding of what kind of conditions the cyclists avoid, answerers were able to determine their cycling season and freely describe conditions that prevent them from cycling. Answers were compartmentalized and then divided in conditions that can not be changed by human intervention and conditions that can be mitigated by human actions. In Table 4 and 5 conditions are presented with their popularity. Numbers are given as how large percentage of answerers mentioned the condition.

Table 4. *Cycling hindering conditions where human interference is possible to improve the driving conditions.*

Human interference possible	
Slipperiness	25%
Snowy streets	23%
No snowplowing done	19%
Sleety streets	16%
Ice	13%
Poor winter management of bicycle roads	6%
Darkness	4%
Bumpy ice	4%
Rubble/large sand on bicyle roads and sanded streets	2%
Not sanded streets	1%
Cycling through city centrum	1%
Frost heave	1%
Narrow motor road as only option	1%

Table 5. *Cycling hindering conditions where human interference cannot mitigate the situation.*

Human interference not possible	
Rain or heavy rain	39%
Coldness	26%
Strong wind	16%
Snowstorm	7%
Sleety rain	5%
Winter	2%
Thunderstorm	2%
Wetness	2%
Heat	1%
Long rainy periods	1%
Frost heave	1%
Only unsafe roadway available	1%

To find out what are the important aspects of route for cyclists, they were given 12 possible features to sort from most important to least important. Based on the answers, a weighted average was calculated for each feature to see which were rated more highly. The weight was dropped by 1/12 with every less important priority placement, starting from weight of 1 for first and most important placement. The weighted averages are shown in table 6. The distribution of placements between different features are shown in figure 16. In line with Van Goeverden's and Godefrooij's recommendations, the fastness of the route is regarded highly by the cyclists, as 30% rated that the most important route quality feature. The length of the route and amount of stops and interruptions are right behind, and while their weighted average is similar, amount of stops and interruptions gets more first and second positions than the length of the route.

Table 6. *Cycling route features sorted by weighted average calculated from their priority placements*

Weighted averages for cycling route features	
Fastness of the route	6,3
Length of the route	5,9
Amount of stops or interruptions	5,9
Road condition	5,8
Amount of traffic	5,2
Height differences	4,3
Road surface material	4,0
Amount of pollution or dust	3,3
Amount of noise	3,3
Interesting places and views by the route	3,3
Amount of services by the route	2,9
Lighting condition	2,7

In addition, the answerers could also in the following open question tell what kind of features they find important or interesting on cycling routes. This was done to survey if the list of twelve route features excluded some important aspect for cyclists. 46 persons provided answer for the open question and the following paragraphs summarize the results.

The most common ones concentrate on the safety and comfort aspects of the cycling. The types of roadway, and specifically the availability of cycle paths was the most commonly mentioned important trait. The availability of cycle paths ties on both of the comfort of driving as well as safety.

Safety itself was also mentioned over 19% of the answers. Often as a general aspect, but some did mention more precise situations such as safe entries to underpasses or blind spots. Regarding the blind spots, mirrors were also mentioned separately as a safety measure.

Along with those major elements, less common but more precise factors were mentioned. Both importance of safe bicycle parking possibilities, be it during workday, near public transportation or nighttime storage for overnight bicycle trips, and clear directional signs were mentioned by 10%.

Pleasantness of the route came up in different answers. There were answers that mentioned environmental pleasantness, such as nice views, presence of nature and noiselessness while

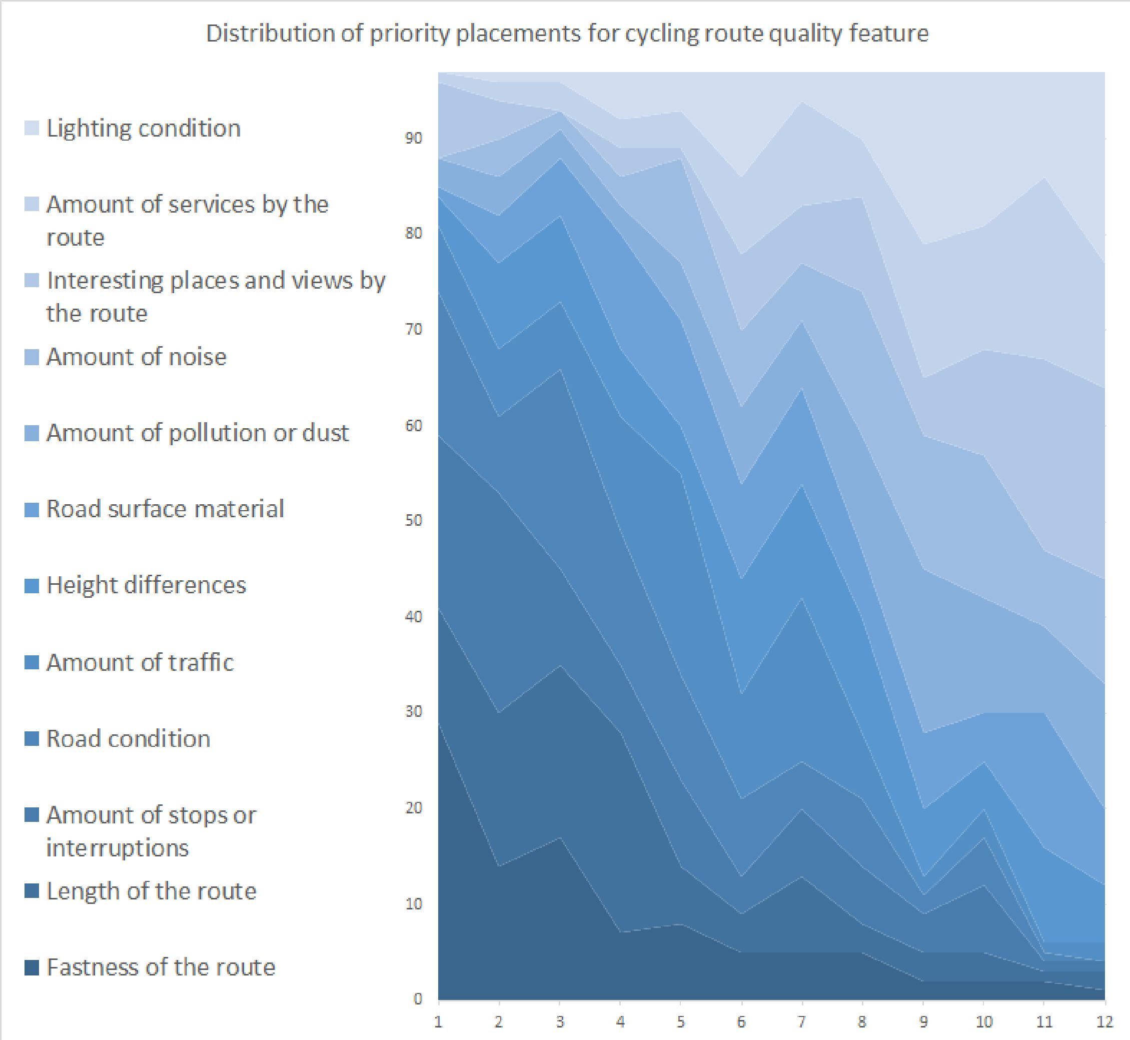


Figure 16. *Distribution of priority placements for cycling route quality features. First position is most important, twelfth the least important feature.*

some answers were more focused on the pleasantness of the cycling: Only few uphills, straight and clear routes and no pavement edges on the route.

Identifying the both detrimental and beneficial factors for cyclists can help when planning what to measure and what kind of information can and should be provided from service that is aimed to help cyclists.

6.2.3 Current supporting devices used by participants

When asked about usage of supporting devices or applications during cycling, 44% of the answerers admitted using one. These devices or applications can be divided in three main categories: Sports applications, personal fitness devices and other measurement devices.

Sports applications are usually used with mobile phones, and they offer services such as gathering exercise habits data, GPS tracking with speed and distance and social features. Personal fitness devices offer more precise personal fitness information, such as heart rate monitoring and calorie calculations. They might also have GPS tracking features and other services, much depending on the device in question. The measurement device category includes speedometers and distance trackers and other accessories that offer information about the cycling but not necessarily about the person riding the bicycle.

6.2.4 Feature and data requests and suggestions for potential services

During the survey, answerers were told general ideas about the "BikeBox": It being a separate device which would measure different environmental characteristics and that the gathered data should be used to make cycling more attractive option. After that answerers were possibility to freely tell what kind of services would encourage them to cycle more and what kind of data they would be interested to see. Many of the 76 answerers mentioned more than one feature, and answers included opinions about the service media, specific data, and additional features.

Most requested data was related to the condition of the cycling roads: 18% of answers mentioned it, with additional 6,6% specifying wintertime road conditions. Related topic was the snow blowing situation during wintertime, mentioned also by 18%. Among the most common requested features were route suggestions, this seemed to have two different flavors: wanting route suggestions for different styles of cycling, such as forest trails or for different difficulties (16%) and wanting to have different navigation options to destination, such as picking fast or scenic route (11%). Roadworks and their effects to the route was requested by 17% and information about amount of stops, such as traffic lights or difficult intersections were requested by 7,9%.

Some of the requested data were more specific features for smart navigation. Most of these got only few, or even one mention so with the data amounts gathered it's difficult to say if they are true outliers of if their interest would hold in same ratio in more extensive survey. These mentions include for example nearby services or interesting destinations, real time sanding situation, personal cycling information and air quality. Some were interested in knowing where other cyclists drive and how other cyclists evaluate routes. Few answerers noted giving open feedback about route quality or forwarding the quality data to maintenance.

Participants were also given four different claims where they could choose between two opposites regarding their preferences for services created from cycling data. They could also select equally interesting if they had no preference over the opposites. Results are shown in Figure 17 as numbers from answers.

Mobile application or at least mobile compatible web page seems most interesting option, even though answerers prefer services that would be used before leaving. Text or notification based solutions did not get much interest, and answerers preferred personalization over generalization.

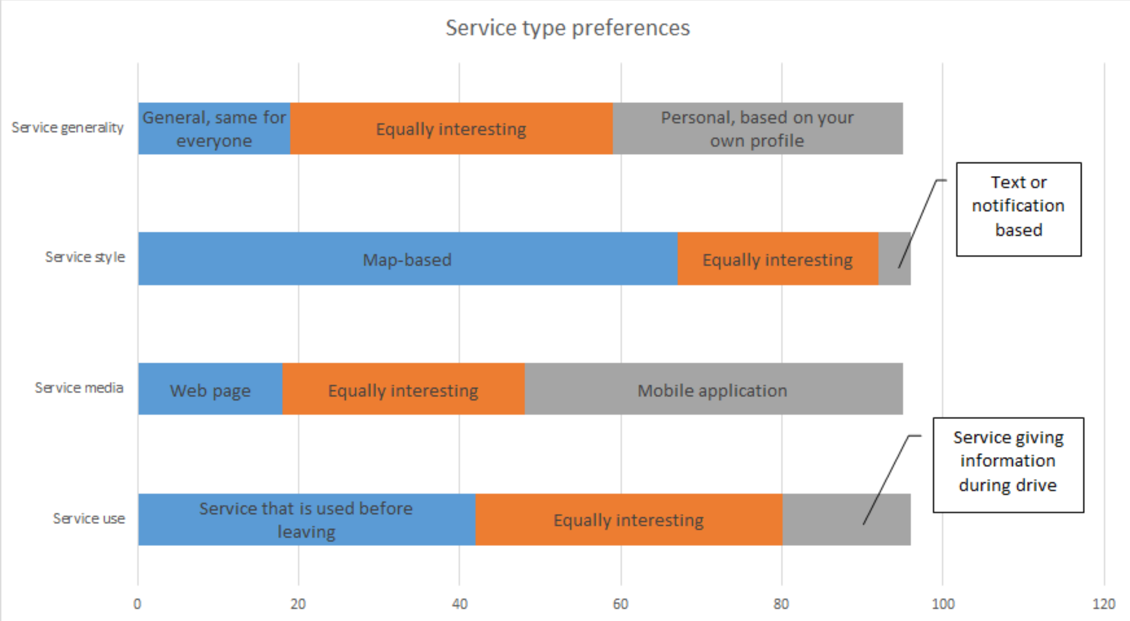


Figure 17. *Service preferences as number from answerers.*

Participants were asked if they would use BikeBox-type of device with two questions separated by if the device would be accompanied by service where user could store and follow their own route data.

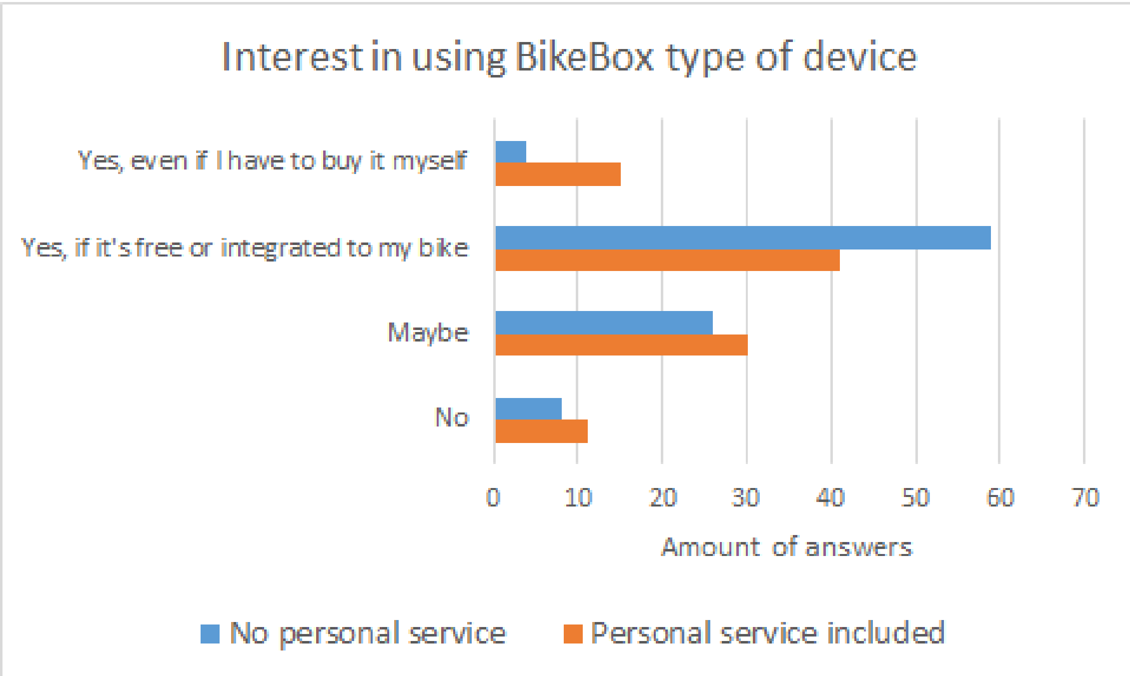


Figure 18. *Interest for using BikeBox type of device.*

Seen from the results in Figure 18, adding the personal service does not sway much the maybe and no answerers, but it does add willingness to purchase such device yourself. Survey participants who chose Maybe or No options were given possibility to explain why. Those answering No mentioned privacy concerns as one reason as well as not seeing personal benefit or use for the device, or being uninterested in general for collecting data from their drive. Maybe- answers noted desire for ease of use in sense of not causing additional work for the user as well as small size and not disturbing the driving. Reliable security and privacy were noted in maybe-answers too, users don't want to be identified from the data or tracked to their home. In addition, answerers wanted the collected data to actually be useful for city maintenance.

7. DISCUSSION

This chapter discusses if the cycling environment measurements can provide data that benefits cyclists with different route features. For the purpose of the discussion, possibility to crowdsource the data is assumed. This chapter also presents two ideas for possible services that use cycling environment data and what is needed in future work.

7.1 Environmental measurements and preferences of cyclists

This section is based on the features presented in Table 5.6, and discusses whether environmental measuring done in this thesis can be used to generate information for cyclists about the cycling route features mentioned in here or if there are other possible sources for the data.

In order to assess how useful it would be to gather environmental measurements from each of the features, in addition to the cyclists priorities, they were evaluated on two additional qualities: Is such data currently available and can the data be useful in city maintenance and planning. Availability of data was evaluated on three step scale: Not available, partially available and widely available, where not available means the highest usefulness as measurements would bring new information. Usefulness for city maintenance and development was also evaluated with three step scale: useful, potentially useful and not likely useful.

Fastness of the route

Current navigation softwares can give approximations of route fastness based on the distance and assumed speed. As discussed in Section 6.1.2, measurements from cyclists that include GPS locations and timestamps can be used to calculate real speeds over the route, which can provide more accurate estimations. Currently this kind of data is not widely available, but as different sport trackers collect cycling speeds, it can be considered to be partially available. While the day to day maintenance about city can not do much with information about the fastness of the route, it could have usage in city planning, examining what kind of traffic solutions give better results, thus potentially useful.

Length of the route

Current navigation and map softwares and services can provide the length information without cycling specific measurements. Crowdsourced GPS information can be used to calculate route distances. On well mapped areas that may not bring extra benefit. However for small or unmapped forest trails, GPS data from other cyclists can provide more accurate description of the route compared to rougher - as the crow flies - estimates. As off-tracks cycling is rarer, relevant data can be considered to be widely available. From the city maintenance and development side, data gathered from route lengths seems to fall in the not likely useful -category.

Amount of stops or interruptions

While some information could be obtained from other sources, such as city's traffic light data, accurate data for slow spots or interruption for especially cyclists can be calculated from crowdsourced measurements that include GPS locations and timestamps, as discussed in Section 6.1.2 in this thesis.

As with fastness of the route, currently this is not widely available, but could be calculated from sport tracker data so data can be considered to be partially available. Information about stops and interruptions could be used to evaluate and adjust traffic light behavior and other traffic flow control mechanisms, making it likely useful for city maintenance.

Road condition

As discussed in Section 6.1.2, observing road condition is plausible by using accelerometers that react to the bicycle's jolting caused by the roughness of the surface, potholes and gravel on ground. If such data is available, cyclists can choose between smoother or rougher terrain areas and cycle where it is comfortable.

Currently this kind of data is not available from cycling roads and it could be used to direct maintenance effort for areas that are commonly used and in need of repair, making it likely useful for city maintenance.

Amount of traffic

The environmental measurements in this thesis do not try to assess amount of non-cyclist traffic, such as cars or pedestrians. Measurements from cyclists could be used to determine amount of cycling traffic.

Currently this kind of data is not widely available from cyclists, though it is possible that sport tracker data could be used for estimating amount of cyclists. Traffic data related to cars is available to some degree, as can be seen from the service of Liikennevirasto, which gives information about traffic situation all around Finland [43]. However, services concentrating on cars might not measure and share information about traffic density on areas that interest cyclists, which is why this is considered to be partially available. The traffic flow and amount of different vehicles around city could be useful as supporting information from city maintenance and planning point of view.

Height difference

The environmental measurements in this thesis do not assess height differences. Current navigation and map services do offer information about height differences, so it can be considered to be widely available. Understanding the topography of city is important for the city planning and maintenance, but for this purpose, cycling environment measurements do not seem to be the most useful source of data.

Road surface material

As discussed in Section 6.1.2, information about road surface can be gathered. However, reliably identifying surface materials from each other would require further analysis and measuring.

Currently the knowledge of different surface material exists at least on major roads, though the availability for public is uncertain. However, for the city, this information should be available and should not require confirmation from cycling environmental measurements, making this not likely useful for the city maintenance.

Amount of pollution or dust

The environmental measurements in this thesis do not assess pollution or dust. As noted in Section 5.1, the dust sensor in prototype did not provide any useful data.

Air quality is monitored in Finland, however, the density of the measuring stations is low, as can be evaluated from air quality service from Ilmatieteenlaitos [39]. Supplementing the official measurements with more local results could offer additional information for city about problematic areas, which can be used to take mitigating actions, making this potentially useful for city maintenance.

Amount of noise

The environmental measurements in this thesis do not assess amount of noise. Noise level is environmental factor that does interest cities, European Noise Directive requires noise assessments to understand the noise and to better plan the city [48]. Thus information about noisy areas could be helpful for city maintenance and planning. Currently noise levels are not widely available, but noise assessments and measuring are being done, so data can be considered to be partially available.

Interesting places and views by the route

Current navigation and map services offer some existing information about interesting places and views by the route, but it could be expanded especially about smaller and local attractions, so it can be considered to be partially available. However, the usability of the information for the city maintenance seems low.

Amount of services by the route

Current navigation and map services offer existing information about services by the route, locations of stores, offices and other services are widely available. The usability of the information for city maintenance seems low.

Route features \ Usefulness factors	Cyclists priority score	Data availability	Usefulness for city maintenance
Fastness of the route	6,3	Partially	Potentially
Length of the route	5,9	Widely	Not likely
Amount of stops or interruptions	5,9	Partially	Useful
Road condition	5,8	Not available	Useful
Amount of traffic	5,2	Partially	Useful
Height difference	4,3	Widely	Not likely
Road surface material	4,0	Partially	Not likely
Amount of pollution or dust	3,3	Partially	Potentially
Amount of noise	3,3	Partially	Potentially
Interesting places and views by the route	3,3	Partially	Not likely
Amount of services by the route	2,9	Widely	Not likely
Lighting conditions	2,7	Not available	Useful

Figure 19. *Usefulness factors for the environmental data collected from the route features*

Lighting conditions

As discussed in Section 6.1.2, lighting condition can be assessed by measuring cycling environment with light sensor. Currently the existence of light fixtures is widely available knowledge, but the real time data of how it matches to the ambient lighting of the environment is not. As the lighting is part of the city infrastructure, up to date information about its quality could be used for maintenance and further development.

Of these, the fastness of the route, amount of stops or interruptions and route conditions are both high in the cyclist preferences and can be measured with BikeBox type of solution. Figure 19 summarizes the usefulness of the potential environmental measurements for the route features discussed in this section.

7.2 Applications from the collected environmental data

Based on the data, two application possibilities were identified: Using the data for smart navigation and decision support for road maintenance.

7.2.1 Smart navigation

Smart navigation refers to situation where in addition to directions based on the road network, the navigation service provider takes additional information, such as road quality, average speeds, elevation, services along the route and other such features into account when determining the most suitable route. Data gathered from cyclists could be used for this purpose, allowing cyclists to determine which factors are more important to them and the route is calculated based on the preferences. For example, during spring time cyclists could prefer swept roads to avoid sanded streets, or choose routes that are less likely to have interruptions. Navigation could also react over time to slow changes. If some roads are getting slower based on the real speed data or if the quality of the road is deteriorating, smart navigation can start to prefer other routes.

Based on the survey, condition of the roads is the topic that interests cyclists. It was quite high in the cycling route features and was also the most commonly mentioned information request. Smart navigation could provide the information, with additional possibility of finding routes that have better quality roads. Additionally, commonly mentioned request was to find different kind of routes, based on difficulty of the route or what kind of environment the route takes. Smart navigation is suitable for this kind of service, though the environmental measurements done in this thesis do not yet cover all the necessary information users would like to have. However, not all data in smart navigation services need to come from environmental measurements as different sources should be combined to provide good service quality.

7.2.2 Decision support for road maintenance

When dividing and channeling limited resources to maintain and fix public areas, having up to date information about usage frequency and different quality metrics can help to direct the resources to places where they are best used. Cycling data could be used as one of the data sources in Smart City, using it for decision making. When road qualities start to decline based on the long term accelerometer data, it can signal maintenance needs. Drastic areal changes in lighting situation can be enough to spot broken lamps which need to be changed.

7.3 Challenges

Accuracy of the GPS location poses challenge for the interpretation of the data. While general trends over larger area are not as problematic, applications that need to pinpoint specific locations, such as broken lamps, suffer from inaccuracies with the location. While it can be assumed that maintenance crew is able to find broken lamp even if the location is off by some meters, real risk is that the problem goes unnoticed when the measurements from light and dark areas end up mingling due to imprecise location.

7.4 Future work

While this work tries to identify the needs and interests of the cyclists using the BikeBox, there are other interest groups for the services that could be created from BikeBox data. One example of such interest groups is the city maintenance. Even if this work presents possible use cases for the data in that context, for feasible and usable solutions it would be necessary to work together with the interest group.

As the results from the prototype test runs show, there are possibilities to identify road surface qualities. In future work it is however required to work out how mass, speed and different bicycles affect the numbers, so that crowdsourced data can be reliably interpreted.

As usability and interest-wise separate devices can be difficult: They will be somewhat expensive purchase to the bicycle user and an additional device to remember and to keep track of. As many modern smart phones have corresponding sensors: accelerometers or gyroscopes and light sensors, it could be useful to investigate if the available sensors could measure the same environmental aspects when mounted on the bike's frame.

If the available smart phone sensors would be sufficient, adopting new application to existing device is less work and expenses for user compared to adopting new device. Possible drawbacks of using smart phone sensors compared to dedicated devices might include being limited by the available sensors in the smart phone, which might have undesirable range or accuracy because manufacturer did not intend them to be used for environmental monitoring. In addition, different smart phones might be using different models of sensors, with different ranges, measuring frequencies and accuracies, which might cause discrepancies between crowdsourcers. For user, the benefit would be usage of existing device with its data plan, no separate SIMs, subscriptions or devices required. However, using the smart phone to measure the cycling conditions user resources of the phone and might cause battery drain or additional data consumption. From user's point of view, separate device running out of battery or monthly data is less problematic than same thing happening for their smart phone.

8. CONCLUSIONS

Interest in cycling is increasing, partly as a environmental friendly and healthy transport option, partly as a solution for the traffic problems large cities face. To create environment that supports and promotes cycling, cities have to understand the needs of the cyclists and keep the cycling infrastructure usable. This created the incentive to find out, if cycling environment can be measured and what kind of information the cyclists need.

In this thesis, a prototype of BikeBox was presented to measure road condition, light situation and possible stopping points along the cycling route. The prototype used accelerometer, photoresistor and 3G/GPS module to measure the environment and match the measurements to GPS coordinates. Data was sent during drive to server over the 3G connection.

The data gathered from test drives shows that it is possible to notice the changes caused by different road qualities with the accelerometer included in BikeBox. This thesis did not try to formulate the mathematical model for classifying the road qualities as it would need further testing to understand how the speed, mass and tyre pressure would affect the measurements. However, it is still possible to visualize the road quality differences by calculating moving window variance from the accelerometer using the axis orthogonal to the ground. Higher variance is observed on areas that have rougher terrain.

In addition to the road quality, the BikeBox set out to identify poorly lit areas. Photoresistor is able to notice the difference, however the inaccuracies of GPS pose challenge when pinpointing small problematic locations. GPS data can be used to calculate the speed of cyclist and allows for recognizing slower and faster areas and areas, where cyclist must wait for prolonged period.

An online survey was conducted for 97 cyclists to find out what are their preferences on cycling routes. The fastness and length of the route, amount of stops and interruptions during it and road conditions were high in the priority. Additionally, safety of the route was deemed important.

Based on the priorities, it is evident that environmental measurements can tell about factors that cyclists deem important. Further study is needed in analyzing how the data can be best utilized and how several sources will affect the data analysis. In addition, it would be advisable to study if smart phones with suitable sensors could be used as the measuring device.

REFERENCES

[1] http://wiki.seeedstudio.com/Grove-3-Axis_Digital_Accelerometer-16g/. [Online, accessed 16-August-2018].

[2] I.T.S.G. 20, Global Information Infrastructure, Internet Protocol Aspects and Next-Generation Networks, International Telecommunication Union ITU, Techn. rep., 2012. http://handle.itu.int/11.1002/1000/11559 [Online, accessed 31-July-2018].

[3] 3G/GPRS shield over Arduino and Raspberry Pi. https://www.cooking-hacks.com/documentation/tutorials/3g-gps-shield-arduino-raspberry-pi-tutorial/ [Online, accessed 13.11.2018].

[4] M. Aalto, Helsingin polkupyöräambulanssi ehtii autoa nopeammin paikalle, ja mukaan mahtuu lähes samat tarvikkeet - ”Kun sydän on pysähtynyt, nopeus on äärimmäisen tärkeää, http://www.hs.fi/kaupunki/art-2000005353634.html. Online, accessed 25-October-2018.

[5] R. Akeela, Y. Elziq, Design and verification of ieee 802.11 ah for iot and m2m applications, in: Pervasive Computing and Communications Workshops (PerCom Workshops), 2017 IEEE International Conference on, IEEE, 2017, Kona, HI, USA, pp. 491–496.

[6] Arduino, Arduino, 2018. https://www.arduino.cc/ [Online; accessed 19-November-2018].

[7] L.L. Arnold, P.A. Zandbergen, Positional accuracy of the wide area augmentation system in consumer-grade gps units, Computers & Geosciences, Vol. 37, Iss. 7, 2011, pp. 883 – 892.

[8] A. Banks, E. Briggs, K. Borgendale, R. Gupta, MQTT Version 5.0, Oasis, Techn. rep., 2018. http://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.pdf.

[9] Bitlock, https://bitlock.co/. [Online, accessed 13-August-2018].

[10] C. Bormann, K. Hartke, Z. Shelby, The Constrained Application Protocol (CoAP), Internet Engineering Task Force, Techn. rep., 2014. https://tools.ietf.org/html/rfc7252.

[11] Bos:311 app. https://www.boston.gov/departments/new-urban-mechanics/bos311-app [Online, accessed 6.11.2018].

[12] S. Brakatsoulas, D. Pfoser, R. Salas, C. Wenk, On map-matching vehicle tracking data, in: Proceedings of the 31st International Conference on Very Large Data Bases, 2005, VLDB Endowment, VLDB '05, Trondheim, Norway, pp. 853–864.

[13] F. Carrera, S. Guerin, J. Thorp, By the people, for the people: The crowdsourcing of "streetbump": An automatic pothole mapping app, International archives of the photogrammetry, remote sensing and spatial information sciences, 2013, pp. 19–23.

[14] K. Chen, M. Lu, G. Tan, J. Wu, Crsm: Crowdsourcing based road surface monitoring, in: High Performance Computing and Communications & 2013 IEEE International Conference on Embedded and Ubiquitous Computing (HPCC_EUC), 2013 IEEE 10th International Conference on, IEEE, 2013, pp. 2151–2158.

[15] H. Chourabi, T. Nam, S. Walker, J.R. Gil-Garcia, S. Mellouli, K. Nahon, T.A. Pardo, H.J. Scholl, Understanding smart cities: An integrative framework, in: 2012 45th Hawaii International Conference on System Sciences, Jan, 2012, pp. 2289–2297.

[16] Copenhagen wheel, https://www.superpedestrian.com/en. Online, accessed 10-October-2018.

[17] Cycliq, https://cycliq.com/. [Online, accessed 13-August-2018].

[18] A. Devices, ADXL345, Analog Devices, Techn. rep. https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL345.pdf [Online, accessed 13.11.2018].

[19] A. Devices, The five motion senses: Using mems inertial sensing to transform applications. https://www.analog.com/media/en/technical-documentation/white-papers/The_Five_Motion_Senses.pdf [Online, accessed 12.11.2018].

[20] S.B. Eisenman, E. Miluzzo, N.D. Lane, R.A. Peterson, G.S. Ahn, A.T. Campbell, Bikenet: A mobile sensing system for cyclist experience mapping, ACM Trans. Sen. Netw., Vol. 6, Iss. 1, Jan. 2010, pp. 6:1–6:39.

[21] Ellipse, https://lattis.io/products/ellipse. [Online, accessed 13-August-2018].

[22] Endomondo, https://www.endomondo.com/. [Online, accessed 10-August-2018].

[23] W.T. Faulkner, R. Alwood, D.W. Taylor, J. Bohlin, Gps-denied pedestrian tracking in indoor environments using an imu and magnetic compass, in: Proceedings of the 2010 International Technical Meeting of the Institute of Navigation, Citeseer, 2010, pp. 198–204.

[24] K. Flüchter, F. Wortmann, Implementing the connected e-bike: Challenges and requirements of an iot application for urban transportation, in: Proceedings of the First International Conference on IoT in Urban Space, ICST, Brussels, Belgium,

Belgium, 2014, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), URB-IOT '14, Rome, Italy, pp. 7–12.

[25] A. Fox, B.V.K.V. Kumar, J. Chen, F. Bai, Multi-lane pothole detection from crowd-sourced undersampled vehicle sensor data, IEEE Transactions on Mobile Computing, Vol. 16, Iss. 12, Dec, 2017, pp. 3417–3430.

[26] A. Gaur, B. Scotney, G. Parr, S. McClean, Smart city architecture and its applications based on iot, Procedia computer science, Vol. 52, 2015, pp. 1089–1094.

[27] GL55 Series Photoresistor Manual, https://www.kth.se/social/files/54ef17dbf27654753f437c56/GL5537.pdf. [Online, accessed 10-November-2018].

[28] C. Gomez, J. Oller, J. Paradells, Overview and evaluation of bluetooth low energy: An emerging low-power wireless technology, Sensors, Vol. 12, Iss. 9, 2012, pp. 11734–11753.

[29] GP2Y1010AU0F Compact Optical Dust Sensor. https://www.sparkfun.com/datasheets/Sensors/gp2y1010au_e.pdf [Online, Accessed 11.11.2018].

[30] B.S.I. Group, Specification of the Bluetooth System, Bluetooth Special Interest Group, Techn. rep., 2016. https://www.bluetooth.org/DocMan/handlers/DownloadDoc.ashx?doc_id=421043&_ga=2.35360993.1755692042.1533020608-329819620.1533020608 [Online, accessed 31-July-2018].

[31] Grove - light sensor, http://wiki.seeedstudio.com/Grove-Light_Sensor/. [Online, accessed 16-August-2018].

[32] J. Gubbi, R. Buyya, S. Marusic, M. Palaniswami, Internet of things (iot): A vision, architectural elements, and future directions, Future Generation Computer Systems, Vol. 29, Iss. 7, Including Special sections: Cyber-enabled Distributed Computing for Ubiquitous Cloud and Network Services & Cloud Computing and Scientific Applications — Big Data, Scalable Analytics, and Beyond, 2013, pp. 1645 – 1660.

[33] D. Guinard, V. Trifa, F. Mattern, E. Wilde, From the Internet of Things to the Web of Things: Resource-oriented Architecture and Best Practices, Springer Berlin Heidelberg, Berlin, Heidelberg, 2011, pp. 97–129. Available: https://doi.org/10.1007/978-3-642-19157-2_5

[34] R.E. Hall, B. Bowerman, J. Braverman, J. Taylor, H. Todosow, U. Von Wimmersperg, The vision of a smart city, Brookhaven National Lab., Upton, NY (US), Techn. rep., 2000.

[35] HeiaHeia, www.heiaheia.com/. [Online, accessed 10-August-2018].

[36] Here. https://www.here.com/en/products-services/here-map-content-suite/overview [Online, accessed 7.11.2018].

[37] J. Huang, F. Qian, A. Gerber, Z.M. Mao, S. Sen, O. Spatscheck, A close examination of performance and power characteristics of 4g lte networks, in: Proceedings of the 10th International Conference on Mobile Systems, Applications, and Services, New York, NY, USA, 2012, ACM, MobiSys '12, Low Wood Bay, Lake District, UK, pp. 225–238.

[38] IEEE, Ieee standard for low-rate wireless networks, IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011), April, 2016, pp. 1–709.

[39] Ilmatieteenlaitos. https://ilmatieteenlaitos.fi/ilmanlaatu?as=Suomi&rs=420&et=graph [Online, accessed 17.11.2018].

[40] The iot connected brompton. https://www.brompton.com/news/Posts/2016/News-Evrythng-IOT [Online, accessed 7.11.2018].

[41] S. Krco, B. Pokric, F. Carrez, Designing iot architecture (s): A european perspective, in: Internet of Things (WF-IoT), 2014 IEEE World Forum on, IEEE, 2014, pp. 79–84.

[42] J. Latvala, Monen pyörämatka karahtaa taas kiville – korjaaja syyttää terävää mursketta, tiemestari renkaita, https://yle.fi/uutiset/3-7855146. Online, accessed 26-October-2018.

[43] Liikennevirasto. https://liikennetilanne.liikennevirasto.fi/ [Online, accessed 17.11.2018].

[44] K. Luukka, Konstruktiivinen tutkimusote. https://metodix.fi/2014/05/19/lukka-konstruktiivinen-tutkimusote/ [Online, accessed 11.11.2018].

[45] T. Luukkonen, K. Vaismaa, https://www.liikenneturva.fi/sites/default/files/materiaalit/Tutkittua/Tutkimukset/2013_safety_in_numbers.pdf. [Online, accessed 22-August-2018].

[46] S. Mathur, T. Jin, N. Kasturirangan, J. Chandrasekaran, W. Xue, M. Gruteser, W. Trappe, Parknet: Drive-by sensing of road-side parking statistics, in: Proceedings of the 8th International Conference on Mobile Systems, Applications, and Services, New York, NY, USA, 2010, ACM, MobiSys '10, San Francisco, California, USA, pp. 123–136.

[47] C. Outram, C. Ratti, A. Biderman, The copenhagen wheel: An innovative electric bicycle system that harnesses the power of real-time information and crowd sourcing, 2010.

[48] F. suunnittelu ja tekniikka OY, FCG suunnittelu ja tekniikka OY, Techn. rep. https://www.tampere.fi/tiedostot/t/HZU6Zmihn/Tampereen_meluselvitys_2017raportti.pdf [Online, accessed 17.11.2018].

[49] V. Parikka, Helsingin keskustaan puskee yhä enemmän jakeluatoja - kaupunki haluaa tilalle polkupyörälähettejä, https://www.hs.fi/kaupunki/art-2000005205950.html. Online, accessed 25-October-2018.

[50] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert, J. Koskinen, Overview of narrowband iot in lte rel-13, in: 2016 IEEE Conference on Standards for Communications and Networking (CSCN), Oct, 2016, pp. 1–7.

[51] J. Schipperijn, J. Kerr, S. Duncan, T. Madsen, C. Klinker, J. Troelsen, Dynamic accuracy of gps receivers for use in health research: A novel method to assess gps accuracy in real-world settings, Frontiers in Public Health, Vol. 2, 2014, p. 21.

[52] A. Schneider, http://www.gpsvisualizer.com/. [Online, accessed 11-May-2016].

[53] Seeedstudio, Grove system, http://www.seeed.cc/grove/, 2015. [Online; accessed 23-November-2015].

[54] Sherlock, https://www.sherlock.bike/en/. [Online, accessed 13-August-2018].

[55] M. Siekkinen, M. Hiienkari, J.K. Nurminen, J. Nieminen, How low energy is bluetooth low energy? comparative measurements with zigbee/802.15. 4, in: Wireless Communications and Networking Conference Workshops (WCNCW), 2012 IEEE, IEEE, 2012, pp. 232–237.

[56] Simcom, Wireless modules / EDGE/ HSDPA 3 - 3,5 G, http://www.simcom.eu/index.php?m=termekek&prime=1&sub=38&id=0000000157, 2015. [Online; accessed 2-December-2015].

[57] Sportstracker, https://www.sports-tracker.com/. [Online, accessed 10-August-2018].

[58] M. Tauber, S.N. Bhatti, Y. Yu, Application level energy and performance measurements in a wireless lan, in: Proceedings of the 2011 IEEE/ACM International Conference on Green Computing and Communications, Washington, DC, USA, 2011, IEEE Computer Society, GREENCOM '11, pp. 100–109.

[59] Telia. https://www.telia.fi/asiakastuki/verkko/verkko/verkkokartta [Online, accessed 12.11.2018].

[60] The Cricket, http://b45h.com/. [Online, accessed 13-August-2018].

[61] S. Tondare, S. Panchal, D. Kushnure, Evolutionary steps from 1g to 4.5 g, International Journal of Advanced Research in Computer and Communication Engineering, Vol. 3, Iss. 4, 2014, pp. 6163–6166.

[62] TUT, http://www.tkt.cs.tut.fi/research/gwg/index.html. [Online, accessed 14-December-2015].

[63] C. Van Goeverden, T. Godefrooij, The dutch reference study: Cases of interventions in bicycle infrastructure reviewed in the framework of bikeability, 2011.

[64] Vanhawk, https://www.vanhawks.com/. [Online, accessed 10-August-2018].

[65] Waze. https://www.waze.com/ [Online, accessed 7.11.2018].

[66] What is lwm2m. https://wiki.openmobilealliance.org/display/TOOL/What+is+LwM2M [Online, accessed 10-August-2018].

[67] Y. Xiao, P. Savolainen, A. Karppanen, M. Siekkinen, A. Ylä-Jääski, Practical power modeling of data transmission over 802.11g for wireless applications, in: Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking, New York, NY, USA, 2010, ACM, e-Energy '10, Passau, Germany, pp. 75–84.

[68] K. Yang, K. Zhang, J. Ren, X. Shen, Security and privacy in mobile crowdsourcing networks: challenges and opportunities, IEEE Communications Magazine, Vol. 53, Iss. 8, August, 2015, pp. 75–81.

[69] W. Yang, A. Bajenov, Y. Shen, Improving low-cost inertial-measurement-unit (imu)-based motion tracking accuracy for a biomorphic hyper-redundant snake robot, Robotics and biomimetics, Vol. 4, Iss. 1, 2017, p. 16.

[70] Zigbee 3.0. https://www.zigbee.org/zigbee-for-developers/zigbee-3-0/ [Online, accessed 8.11.2018].

[71] Zigbee pro. https://www.zigbee.org/zigbee-for-developers/zigbee-pro/ [Online, accessed 8.11.2018].